EFFECTS OF FLOW DIVERSION ON DOWNSTREAM CHANNEL FORM IN MOUNTAIN STREAMS

by

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Abstract

This paper reports on a study of flow regime, bedload transport, and channel morphology in diverted and free-flowing segments of mountain streams in Colorado where flow has been diverted, in some cases, for up to one hundred years. The goal of the project was to determine whether differences in channel form and processes could be detected and linked to changes in flow regime from diversion. Intuitively, bedload transport rates are diminished under reduced flows and formerly active surfaces are colonized by vegetation. However, the main premise of this investigation is that the magnitude and type of response is largely influenced by flow hydraulics and channel morphology which control bed mobility and the ability of the channel to alter it's form. Channels of different mobility are expected to respond at different rates to reduced flows. A classification based on valley floor constraint, useful for describing channel processes and predicting response, is introduced.

The effects of diversion on flow regime can vary considerably between individual streams. Typically, the total annual water yield is drastically reduced by diversion, though,where storage is limited, occasional high flows, with a five-to-ten year return frequency, move through the natural channel. These larger events have the potential to reset changes in morphology incurred during the intervening dry years, such as channel narrowing and fining of bed size distribution.

In general, changes in channel capacity were quite subtle and undetectable using hydraulic geometry. The most readily apparent change was a decrease in channel width due to vegetation invasion on gravel bars and the development of a low bank beneath a former cut bank. Response was limited to channel segments flowing through wide valley floors with gravel to cobble beds, slopes ranging from 1 to 2 percent, and banks vegetated by grasses and willows. Here, partial bedload transport occurs under reduced flows; continued movement of mobile bed material through the central portion of the channel while the lateral surfaces remain immobile are the

primary mechanisms by which the reduced flow alters channel capacity. Bedload transport was marginal in segments flowing through in narrow valley floors with large boulders, steeper slopes, and banks under forested cover. Though the steep channel has potential for high transport, much of the stream energy is lost to spill and form resistance from large roughness elements. No change in morphology was apparent in these constrained channels as the entire channel bottom is inundated over a wide range of flows, leaving no lateral surfaces exposed. Some adjustment may occur under the present diversion scenario, though it may take a longer time frame than considered here.

The results presented here are preliminary as of December 1993. Final results will be presented as part of a doctoral dissertation in 1994 and subsequent publications. Additional sampling of bedload transport and velocity were conducted during the summer runoff season in 1993 and are planned for 1994. Results from three years of bedload sampling during peak flow events will be detailed in future publications.

I. Introduction

Many headwater steams in the Colorado Rocky Mountains have been diverted and the water transported to the Front Range for agricultural, industrial, and municipal purposes. Historically, these streams have been diverted without considering the effects on the physical and biological characteristics of the losing channel. Potential impacts include altered flow regimes, depleted stream flow, reduced channel capacity, lowered water tables, encroachment of upland vegetation into riparian areas, and degradation of fish and wildlife habitat. Recently, pressure to maintain flow instream to prevent channel degradation has increased, as indicated by legal disputes and water policy reviews in several western states, including Colorado (Colby, 1990). However, the issues involving instream flows and off-stream water rights are difficult to resolve as the suite of processes which shape and maintain high gradient channels is poorly understood. In this study, the morphological, sedimentological, and hydraulic characteristics of small, steep channels are examined to determine whether changes in channel form and processes are detectable where flow has been diverted.

The extent to which diversion affects channel form depends, in part, on relative changes in flow patterns including the total amount of water diverted, changes in peak and sustained flows, and the length of time a channel has been dewatered. Typically, the rate of sediment transport is diminished under reduced flows and formerly active channel surfaces are stabilized by vegetation. The result should be reduced channel capacity and changes in vegetation growth patterns. However, the magnitude and type of channel change is largely a function of local geomorphic and hydraulic controls or *boundary conditions*, such as the relative mobility of bed and bank materials, the timing, amount, and size of sediment supplied to channels, and the presence of large woody debris and live riparian vegetation. This study focuses on the interaction between water and sediment within the constraints of such boundary conditions in evaluating the impacts of diversion on channel morphology.

Several case studies have documented changes in channel form due to altered flow regimes from both damming and diversion over the past 50 years (Petts, 1979; Graf, 1980; Williams and Wolman, 1984; Andrews, 1986). Most focus on changes due to storage and flow regulation after closure of large dams, though smaller systems have more recently been assessed. However, while both damming and diversion alter the flow regime, there are differences in the effect on runoff patterns. Damming typically reduces flood peaks and increases low flow, providing a more steady mean daily runoff downstream of the structure; the annual yield remains similar to the unaltered yield. Diversion may reduce the mean daily runoff and annual yield, though occasional high flows move through the natural channel, usually during high runoff years when water demand is low. As a result, the movement and storage of sediment is likely to be affected in different ways. The results of studies on the morphologic effects of dams cannot simply be extrapolated to diverted systems with minimal storage.

Much of the research specific to diverted streams focuses on larger (> 20 meters wide) rivers (e.g. Kellerhals and others, 1979), which vary considerably in scale and character from small, steep, narrow streams. Studies have been conducted more recently in smaller streams in California, though much of this addresses specifically the effects on aquatic habitat and vegetation (e.g. Kondolf and others, 1987; Abell, 1989) rather than channel morphology. Other effects have been described in Environmental Impact Statements and project reports (e.g. Vandas and others, 1990; Wesche, 1991; ERO Resources Corporation, 1986); there is, however, a notable reliance on empirical methods in these reports. The proposed research differs from the cited studies in that it employs process-based methods specific to gravel- and boulder-bed streams to assess changes in channel form and processes due to flow diversion.

The parameters examined in this study include width or cross-sectional area, bed particle size, bed topography or channel units, flow velocity or shear stress, and bedload transport rates. Most are common to the study of fluvial geomorphology and require no further definition. However, channel units, described most recently by Grant and others (1990), are features specific to mountain streams and require some explanation. The classification is based on visual interpretation of water surface slope, relative roughness, degree of step development, and percentage of area in supercritical flow during low flow. Types of channel units include pools, riffles, rapids, and cascades; secondary units include log, boulder, and bedrock steps and woody debris jams. *Pools* are relatively deep with minimal slope, low relative roughness, and surface areas free of supercritical flow. *Riffles* are shallow bed features which have steeper slopes and greater surface instabilities than pools (10 -15% of surface area). *Rapids* have more extensive surface instabilities (15-50 %) and are steeper and rougher than riffles; they commonly have irregularly spaced step-pool topography. *Cascades* are the steepest channel unit, with well defined step-pool sequences and more than 50% of the surface area in supercritical flow. Channel units are at least one channel width in length. *Log, boulder,* and *bedrock steps* are less than one channel width in length, but include a significant break in water surface slope. *Woody debris jams* range from a few to hundreds of pieces and also provide a significant break in the water surface slope. The classification has been used for several investigations with reasonably good agreement between units delineated by different persons (Grant and others, 1990).

The specific research objects for this study are as follows: (1) how diversion alters flow regime; (2) whether quantifiable differences in initial boundary conditions exist between subalpine channels; (3) whether processes, including flow hydraulics and bedload transport, differ between channels with different boundary conditions; (4) whether rates and timing of bedload transport differ between diverted and undiverted channel segments; and (5) whether channels of varying initial boundary conditions respond differently to reduced flows.

II. Study Sites

Eight streams, all headwater streams in the Colorado River Basin, were selected for a reconnaissance survey during July-September 1991, including St. Louis Creek, West St. Louis Creek, East St. Louis Creek, and Vasquez Creek, all near Winter Park; Williams Fork River near Parshall; Missouri Creek near Red Cliff, Main Stem Colorado River near Grand Lake; and Fryingpan River near Carbondale. Selection criteria included basin size, diversion history, length of gage record, and accessibility. Average catchment area was approximately 75 km^2, though a range of areas and stream orders (2nd - 5th) were included in the inventory. Each has been diverted for at least 20 years and is gaged. All streams border the Continental Divide and study sites ranged from 2700-3000 meters in elevation.

St. Louis Creek, located on the Fraser Experimental Forest (FEF), has relatively long and continuous gaging records and was selected for a more intensive study on flow dynamics and sediment transport. The catchment is approximately 85 km^2 above the USGS gage and has been diverted by the City of Denver since 1956. Flow is removed at eight sites, indicated on Figure 1 by dashes, and is gaged at five sites (among others) indicated by black circles. The study segments, outlined by solid lines, are contiguous sections of channels of varying morphologies and diverse flow hydraulics. The diverted study site begins where East St. Louis Creek enters the main stem and extends upstream approximately 2400 m. The free-flowing site begins approximately 150 m above the diversion dam on the main stem and is 1200 m in length. Numbers on location map depict sediment transport study sites within diverted and free-flowing segments.

All study channels are located within the subalpine ecotone and are characterized by steep slopes (between 0.01 and 0.12), with beds composed of gravels, cobbles, and boulders derived from Quaternary glacial outwash and tills; streams in smaller basins commonly flow directly on granite or schist bedrock for some length of channel. Mass wasting processes are relatively limited

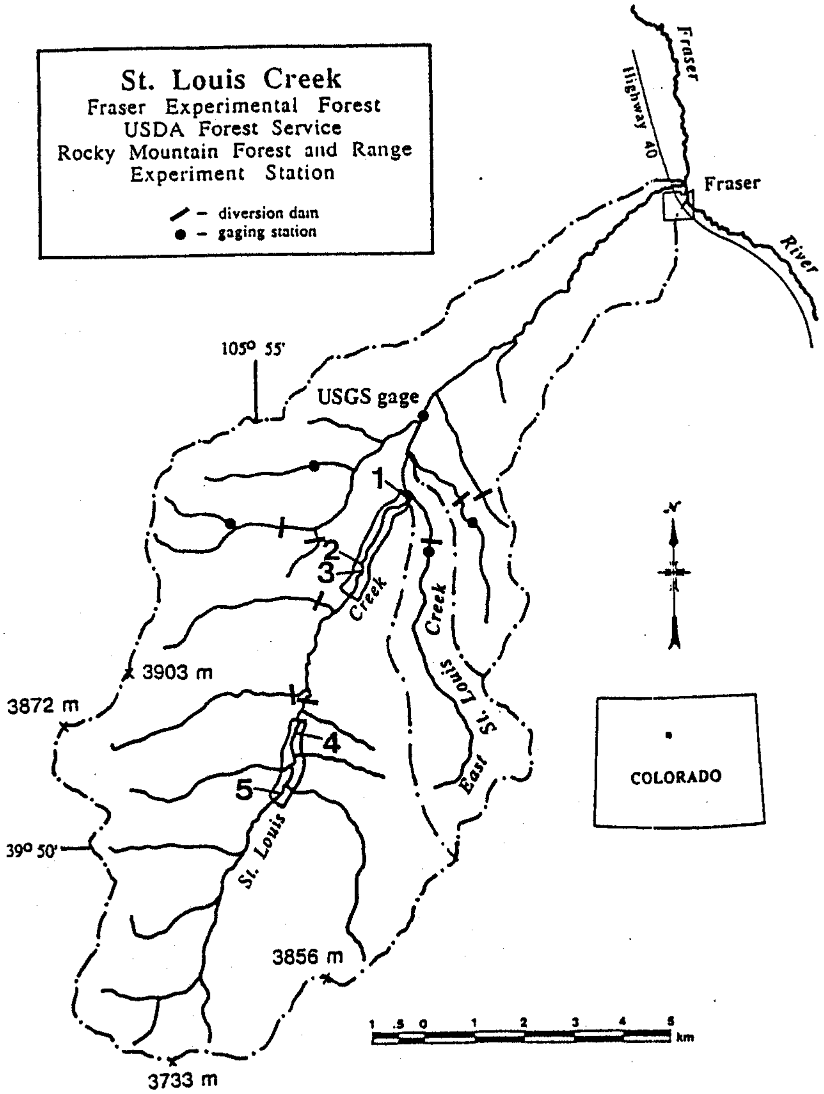


Figure 1. Location map of St. Louis Creek study sites.

(Caine, 1986) and bedload is derived primarily from bank erosion and channel scour. Banks are stabilized by riparian vegetation including subalpine tree species, willows, and grass mats. Bogs and seeps occur along the channel margins within willow carrs. Beaver dams and ponded water are common and affect local flow hydraulics; perched water tables and saturated soils also occur in the riparian zone.

The average yearly temperature recorded at the FEF (which at 2743 m is considered representative of other sites) is 2° C with a mean January temperature of -9° C and a mean July temperature of 13° C. The average annual precipitation at FEF is 610 mm, ranging from 380-760 mm; two-thirds of the precipitation falls as snow. Ninety-five percent of the stream runoff is derived from snowmelt while the remaining five percent is derived from summer rainfall (Garstka and others, 1958). Peak flow occurs most predictably in mid-June. The sites, with the exception of one, are administered by the USDA Forest Service, Arapahoe, White River, and Routt National Forests. The headwaters of the Colorado River in Rocky Mountain National Park are administered by the USDI National Park Service.

III. Methods

3.1 Reconnaissance Surveys--

A reconnaissance survey of diverted streams was conducted during summer low flow in 1991 primarily to detect gross differences in cross-sectional features between populations of diverted and free-flowing channels. The information was also used to describe the range of channel and valley floor features, determine the relationship between valley floors and channel types, and establish a stream classification. Site selection was based on location relative to diversion sites, channel and valley floor characteristics, accessibility, and presence of other land uses. Areas with dams, fish structures, campgrounds, mining operations, and privately-owned lands were avoided. Much of the area in and around the channels and valley floors had been selectively cut at some point in time, making the avoidance of harvested areas impossible. Control segments above diversions were surveyed on all but the Colorado and Williams Fork Rivers; no portion of these channels are unaffected by diversion as the very first tributaries are tapped.

Water surface slope and stationing were established during low flow using a 30 meter tape and hand-held level. Segments were tentatively classified using qualitative criteria such as relative bank stability and valley floor constraint, size of bed material, slope, and vegetation type. Channel portions with similar degrees of constraint of 200 - 500 meters in length were termed "sections". The qualitative assessment was made to ensure a variety of channel types were included and to establish a stratified sampling scheme.

"Reaches", or areas of similar hydraulics and roughness 20-80 meters in length, were established within each section using a quasi-random sampling scheme. Reaches were located 100 to 200 meters apart in channels flowing essentially parallel to the direction of the valley floor. A total of sixty-six reaches were surveyed and the following information collected:

(a) one to three cross-sections measured at relatively 'uniform and steady' locations;
(b) evidence of step-pool formation;
(c) roughness estimate based on Cowan (1956) and Barnes (1967);
(d) estimate of valley floor constraint;
(e) classification of riparian vegetation based on percent basal area covered by trees, willows, or herbaceous species;
(f) number of pieces of woody debris greater than 6" (15 cm) in diameter;
(g) number of boulders greater than 0.5 meters in diameter;
(h) Wolman (1954) pebble count using 100 bed particles;
(i) estimate of percent stream surface area in supercritical flow.

Measurements of channel bottom elevation and estimates of particle size class (in addition to Wolman counts) were sampled at 1 meter intervals at each cross-section; heights and widths of valley floor surfaces and slope breaks were also measured. Measurement ended at the "valley wall", defined by a landform usually composed of large boulders, such as a moraine, outwash terrace, landslide, alluvial fan, or bedrock wall. The bouldery or bedrock form is derived from former climatic controls and is not influenced by the current flow regime, except where the current channel cuts into a older surface. Vegetation type (forest, willow, herbaceous species) was described for each surface or slope break. Rocks on small (1 foot in diameter) portions of gravel bars in St. Louis, East St. Louis, West St. Louis, and Vasquez Creeks were painted and photographed in 1991 and re-checked in 1992 to detect particle movement. Similar methods were used above and below diversion.

3.2 Channel Unit Topography --

Approximately 500 channel units were classified in constrained and unconstrained segments of St. Louis Creek using the methods of Grant and others (1990) described earlier. After classification, low flow widths, estimates of active and bankfull surface width, slopes, and lengths of individual units were measured. Number of boulders greater than 1 meter and pieces of woody debris greater than 15 cm (6 inches) in diameter were tallied for each unit. Information on the patterns and types of channel units was then correlated with valley floor data previously collected.

3.3 Bedload and Velocity Measurements --

Bedload movement and velocity were measured on a near daily basis in St. Louis Creek at five cross-sections during peak flow in 1992. Measurement began in late May and extended until mid-June to ensure that the rising limb, peak, and falling limbs of the seasonal hydrograph were assessed. Two free-flowing sites and three diverted sites were selected to ensure that channels with similar slopes, channel units, particle sizes, vegetative cover, and valley floor constraint were used, minimizing the variance caused by boundary conditions. Velocity and bedload movement were sampled at ten to twelve "verticals" at equidistant locations within the cross-section. Sampling began in the afternoon and ended with the daily peak occurring between 7-9 PM. Flow velocity was measured using Price and pygmy current meters both near the bed and at 0.6 times the depth (assumed to be the average velocity at that vertical); velocities measured with the two meters were within 1-5%, well within the accuracy necessary for this investigation. Bedload movement was sampled using a 3 x 3 inch (7.6 x 7.6 cm) Helley-Smith bedload sampler held in place for one minute at each vertical. Each bedload sample consisted of material collected at all verticals composited into one sample.

3.4 Sampling of Bed, Subsurface, and Bank Material –

Sediment from channel beds, subsurfaces, and banks were collected from St. Louis Creek for comparison with bedload transported by the flow. Bed material was sampled using a Wolman (1954) count of 400 particles per reach. 400 particles were used instead of the traditional 100 to more precisely determine the particle size distribution. Subsurface material was sampled on exposed channel surfaces in unconstrained reaches by carefully scraping away the armour layer and excavating particles immediately below the surface with a shovel. At least one bank per study reach was excavated and samples collected where a visual change in texture occurred.

3.5 Discharge Records--

While analysis of field data will verify changes in channel form, an evaluation of flow pattern is necessary for explaining the processes involved. Records of diverted water volumes are poor or incomplete for most streams, making the rebuilding of the flow record difficult. Fortunately, the flow record can be reasonably estimated for St. Louis Creek by comparison with one of its gaged tributaries. The USGS began monitoring yearly discharge on St. Louis Creek in 1935 and the USFS began seasonal operation of a gage on East St. Louis Creek in 1944. Correlation between the two records between 1944 and 1956, when diversion began, is well suited for purposes of estimating the amount of flow removed seasonally. The effects of diversion on annual and peak flows were evaluated and tested using time-series analysis of pre- and post-diversion flow records and regression analysis with the East St. Louis gage (Haan, 1977; Bras and Rodriguez-Iturbe, 1985).

3.6 Sedimentological Analyses-

Particle size analysis was conducted on materials captured in the Helley-Smith sampler and excavated from channel banks. After samples were air dried at 35° C, large organic matter was removed by picking, blowing, and vacuuming via the Kihl extraction method (Rolf Kihl, personal communication, 1992). All material coarser than 2000 microns was sieved using 1/2 phi interval sieves and the fractions weighed. Material finer than 2000 microns was sample split to approximately 25 grams to obtain a representative subsample, then sieved. Since, presumably, particles finer than 0.25 mm are not trapped efficiently by the Helley-Smith bedload sampler, the weight of finer material was included in the total weight but was not sieved into separate fractions. Particles less than 0.25 mm composed less than 1% of the sample weight.

IV. Results

4.1 Effects of Diversion on Flow Regime: an Example from St. Louis Creek

The effects of diversion on flow regime can vary greatly between catchments due to a number of factors, adding further indeterminacy to the general question of how channels respond to diversion. For example, changing needs during wet and dry years in Eastern slope cities greatly influences the demand for water from Western slope catchments. Flow records must, therefore, be examined on an individual basis to determine how the flow regime is altered. Ideally, records from the unaltered period are evaluated to separate natural flow variability, such as the length of drought periods and the frequency of peak events, from that imposed by diversion. Unfortunately, this information is frequently unavailable, especially for streams with long histories of flow manipulation. In many cases, the impacts of diversion must be estimated using data from nearby gages or regional flood frequency analysis (Potter, 1987).

Differences in the annual runoff, seasonal yield, peak flow and sustained high flow were examined using data from St. Louis Creek to provide an example of diversion impacts on various portions of the flow regime. The average annual runoff measured at the USGS gage prior to diversion was ~32,500,000 m^3 (26,400 acre-ft). The average annual runoff after diversion was ~18,016,000 m^3 (14,606 acre-ft), a reduction of 45% (Figure 2). The means of the two records were significantly different at the $\alpha = 0.01$ level. Reductions of similar magnitude were reported on Vasquez Creek (60±20 %), Fraser River (57± 18%) and Colorado River (38±12%) (based on several years worth of diversion records published in USGS water resources reports). Additionally, the coefficient of variation for St. Louis Creek increased from 20% to 43% indicating the year-to-year discharge has become more variable. This is due primarily to a decrease in the magnitude of the low runoff years rather than an increase the high runoff years. Apparently, during low flow years, when there is no physical restriction from the diversion system, the entire claim can be removed, leaving a relatively depleted channel downstream. Conversely, the volume diverted during a high runoff year is restricted by the physical size of the diversion pipes and tunnels; any surplus water is routed back through the natural channel at higher than normal rates for the diversion period. Again, similar patterns were noted on other diverted streams in the region.

Over time the amount of flow diverted may increase or decrease as, for example, water rights are taken over or given up or as demand changes. However, as complete diversion records are rarely published with other flow data, it is difficult to determine the rate of flow removed and track trends over time. In this study, diversion yield from St. Louis Creek above the USGS gage was estimated through regression analysis with gage data from East St. Louis Creek (ESLC). The ESLC gage is operated seasonally so only flows recorded from May through September were used. However, the analysis provides a suitable estimate of volume diverted during the most critical portion of the year in terms of channel maintenance. Using the regression equation:

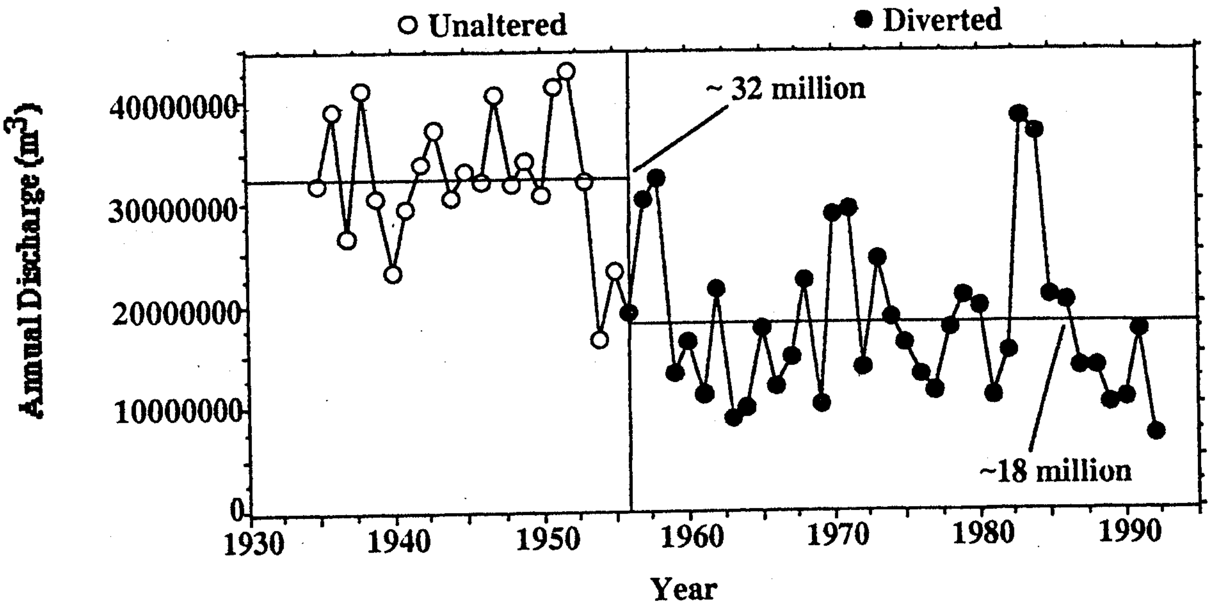


Figure 2. Change in mean Total Annual Yield attributable to diversion, St. Louis Creek, 1935-92.

$$y = 10.50x - 29883.19 \qquad (1)$$

y = estimated *seasonal daily mean* at the USGS gage
x = recorded *seasonal daily mean* at ESLC gage

$r^2 = 0.945$

the expected "normal" discharge was determined by first calculating a value for the Seasonal Daily Mean then multiplying this value by the number of operational days (usually 153) to obtain the *estimated* Total Seasonal Discharge. This value was then subtracted from the *recorded* Total Seasonal Discharge to predict the flow diverted seasonally (Figure 3). The model values for the unaltered period are within 2-12% of the values recorded at the USGS gage; the error estimates for the diverted period are within this range as well. A second-order polynomial equation was fitted to the data (after removing the value for 1958 as minimal flow was diverted that year) to show the long term trend in diversion yield. It appears that the highest yields were obtained in the late 1950's and early 1960's then declined in the mid-1970's. This probably reflects a decrease in demand as additional water projects were brought on line. More flow has been diverted since the mid-1970's, probably in response to increasing demands on existing sources while fewer new projects were started.

Perhaps more critical in terms of channel maintenance are the effects of diversion on the peak flows. As runoff patterns are controlled by climate and basin features, some description of the runoff characteristics of subalpine systems is needed before the impacts of diversion can be addressed. Runoff in streams above 2300 m (7500 ft) is derived primarily from snowmelt, with only minor contributions from rainstorms (Jarrett, 1990). Due to physical limitations on the ablation of snow, such as depth of snowpack and insolation, snowmelt regimes typically have smaller peak flows and lower year-to-year variability compared to rainfall regimes. The highest discharges in subalpine streams are usually only 2-3 times the bankfull flow (Andrews, 1984), whereas floods in rainfall regimes may be an order of magnitude or more greater than bankfull (Pitlick, 1988). The unaltered flows at St. Louis Creek follow a pattern typical of subalpine

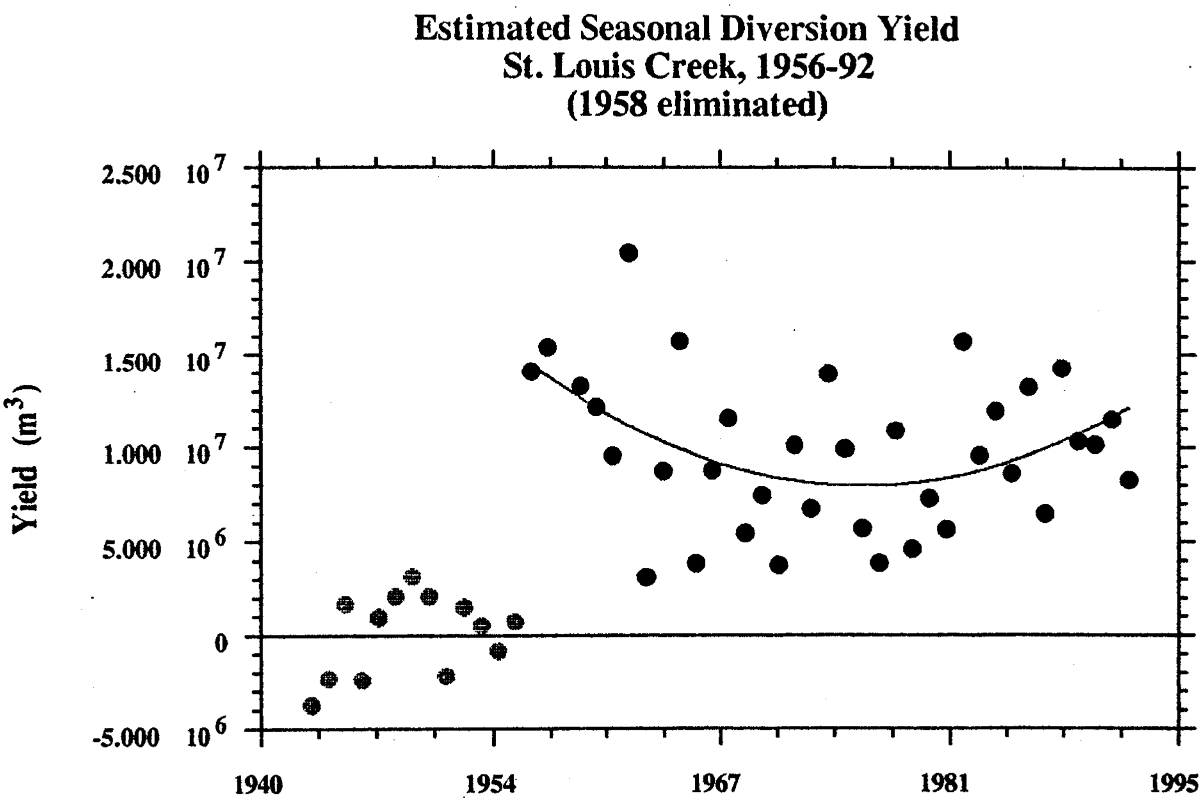


Figure 3. Estimated seasonal diversion yield from St. Louis Creek, 1956-92. Estimate based on regression model using flow data from East St. Louis Creek.

systems as the 100 year flood is roughly twice the bankfull flow (estimated by 1.5 year return interval) (12.57 vs 6.40 m^3 s^{-1}, Figure 4). Also note that the 25, 50, 100, and 200 year floods are nearly equal as the curve becomes asymptotic at higher discharges. Flood frequencies were calculated using *Log Pearson Type III* method (Benson, 1968) on mean daily peak.

The flood frequency curve for the diverted period shows the greatest impact on the magnitude and frequency of low flows. For example, the magnitude the 1.5 year flow is reduced by nearly half (6.40 m^3 s^{-1} to 3.36 m^3 s^{-1}) through diversion. Expressed differently, the unaltered bankfull flow is reduced to a return frequency of once occurrence in 4 years. The unaltered and diverted curves cross at the 10 year recurrence interval, indicating limited impacts on the higher flows. Changes in the upper portion of the curves are due to differences in the means and standard deviations used to calculate the flood frequency and do not reflect a physical change in magnitude.

Bedload transport in subalpine/alpine regions are close-to-threshold events -- that is little movement occurs until threshold conditions are met (Andrews, 1983). Beds tend to remain intact until the armour layer is disturbed and particles of all sizes begin to move, occurring approximately at bankfull (Li and others, 1976; Andrews, 1980). Hence, the period of time conditions are at or above bankfull is critical for channel maintenance; this period of sustained high flow is defined here by the number of consecutive days bankfull flow is exceeded. Comparisons before and after diversion show a dramatic reduction in frequency of days at or above bankfull since 1956 (Figure 5). Prior to diversion, bankfull was exceeded ~ 6 days per year (1.5% of the time). After diversion, bankfull rarely was achieved, with the exception of a few very wet years. During the periods 1960-69, 1973-82, and 1986-1992, (a total of 27 years) bankfull was reached or exceeded only 8 times.

To sum, the total annual water yield from St. Louis Creek has been drastically reduced through diversion, with an increasing trend in the seasonal diversion occurring since mid 1970.

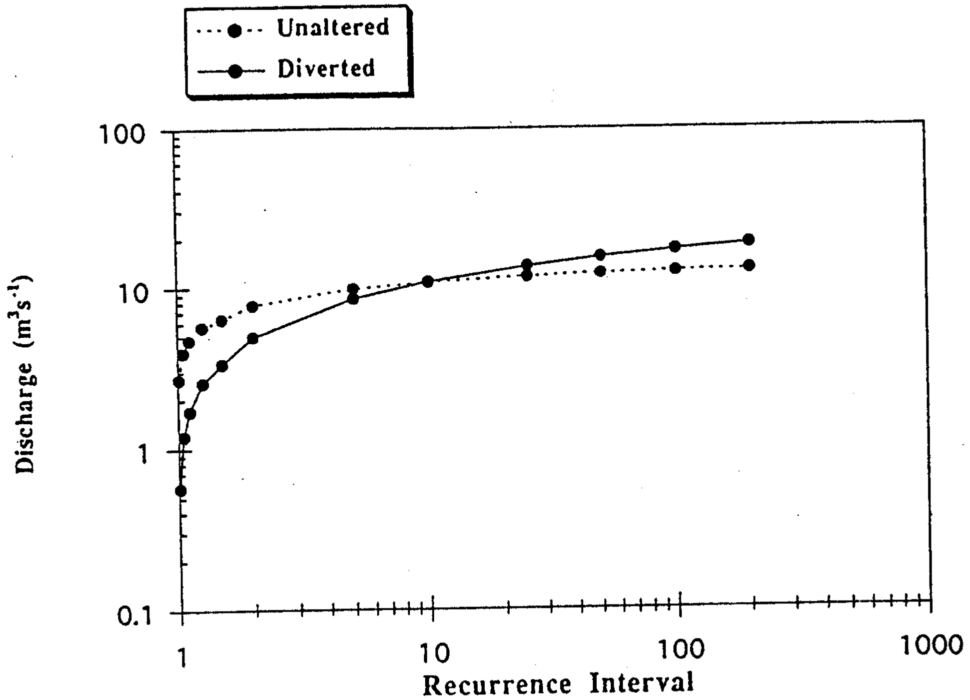


Figure 4. Flood frequency curves calculated using unaltered and diverted flow data from USGS gage at St. Louis Creek (09026500).

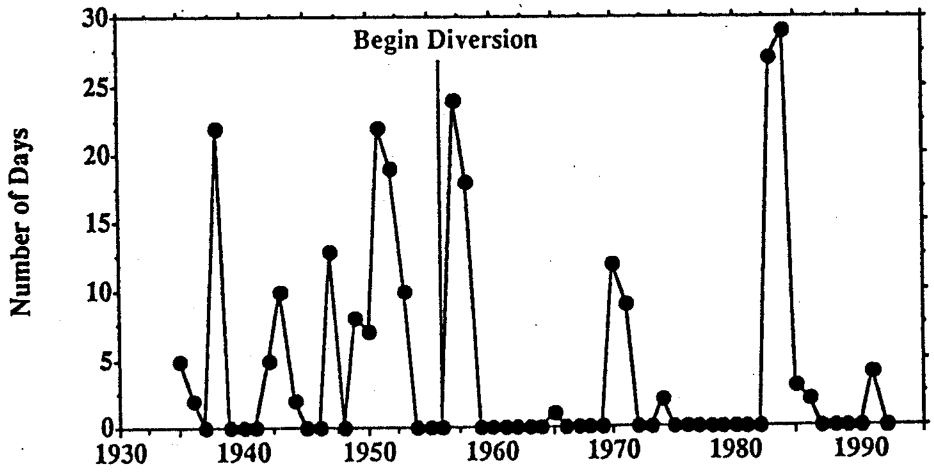


Figure 5. Change in total number of consecutive days bankfull flow reached or exceeded at St. Louis Creek. Bankfull estimated using 1.5 year return interval of 6.4 $m^3 s^{-1}$. Average number of days exceeded in unaltered period is 5.95.

Additionally, the frequency of bankfull or critical transport events has decreased, though occasional high flows, with a five-to-ten year return frequency, continue to move through the natural channel. It is conceivable that channels will show signs of adjustment where threshold flows are infrequently achieved. However, the type and magnitude of response is expected to vary, given the wide variety of channel types observed in this study. A classification useful for describing flow hydraulics and transport processes and predicting response is presented in the following section.

4.2 Characteristics of Subalpine Streams --

Considerable variation in channel features exists in subalpine streams, as indicated by the range of geomorphic and hydraulic variables listed in TABLE I. Though part of this variability results from measuring channels from different size catchments, striking changes frequently occur over short distances within the same catchment, as exemplified by Figure 6. At least four channel types can be identified over a 1.2 km section of St. Louis Creek, based on differences in riparian vegetation and channel width. Here the width is influenced by several factors including endogenous controls, such as introduction of flow and sediment from tributaries, and exogenous factors such as woody debris loading from an ancient landslide. In a broader picture, however, channel features are largely related to the characteristics of the valley floor. The relationship between channels and valley floors are examined in more detail as it forms the basis for much of the remaining analyses.

Table I. Geomorphic and Hydraulic Features of Subalpine Stream Channels

Feature	Mean	Minimum	Maximum	Standard Deviation
Water Surface Slope	0.033	0.005	0.123	0.025
Average Depth (m)	0.43	0.24	0.85	0.134
Bankfull Width (m)	8.3	2.0	18.8	3.4
Valley Floor Width/ Bankfull Width Ratio	8.7	1.7	32.7	5.9
% Supercritical Flow	28.1	5	70	16.4
Logs/square m.	0.069	0.003	0.454	0.009
Boulders/square m.	0.158	0.0	0.98	0.192
D50 (m)	0.121	0.053	0.218	0.041
D84 (m)	0.254	0.105	0.486	0.093
D95 (m)	0.334	0.131	0.702	0.134

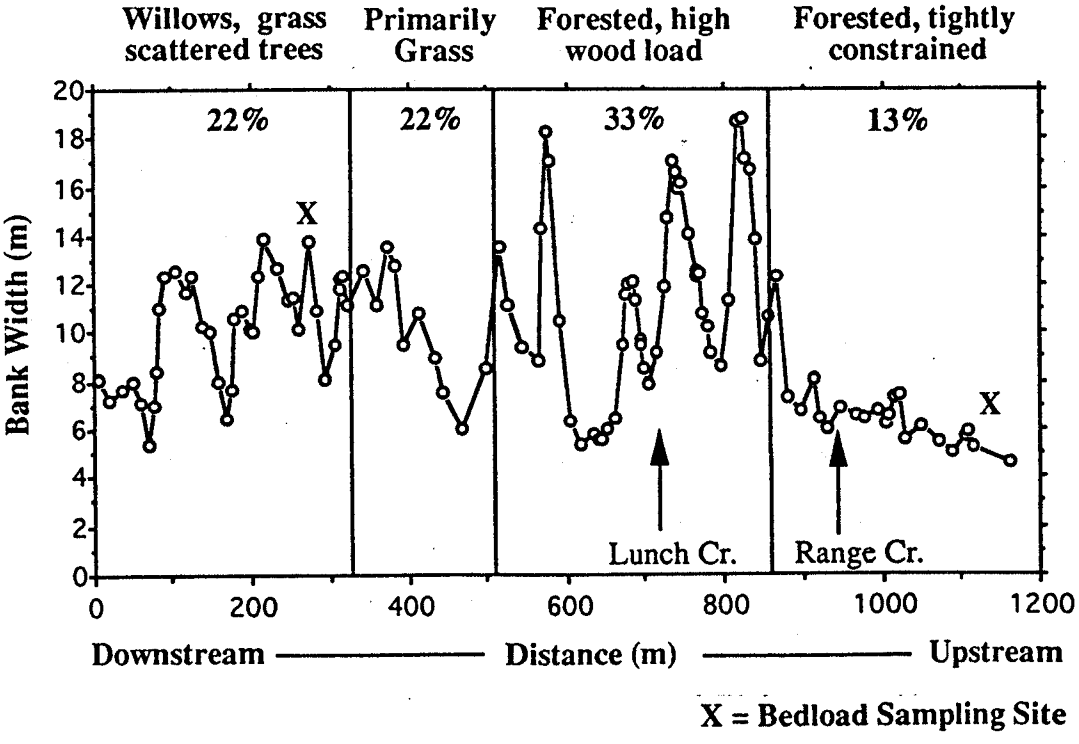


Figure 6. Changes in channel width and riparian vegetation along a 1.2 km free-flowing transect, St. Louis Creek. Bold numbers are coefficient of variability.

Two main channel types were identified in a reconnaissance survey of mountain streams in Colorado: 1) *constrained* channels which flow in narrow valley floors, tightly bound by the valley walls with limited opportunity for gravel bar or terrace development, and 2) *unconstrained* channels, which flow through wider valley floors with greater potential for lateral shifting and room for gravel bar establishment (Figure 7). Constrained channels are dominated by boulder beds and steeper slopes (> 0.04) and commonly exhibit a step-pool topography. Unconstrained channels have gravel to cobble sized bed material, less steep slopes (0.01 to 0.02) and pool-riffle topography. The two are related spatially as narrow valley floors alternate with wide to form an irregular "chain-link" pattern in plan view. The position of constrained segments is controlled by the distribution of tributary fans, ancient landslides, moraines, and outwash terraces. The frequency of unconstrained reaches increases downstream as the stream moves into larger basins, while the frequency of constrained channel increases upstream.

Several multivariate statistical methods were used to classify channels and corroborate the initial field classification. Of the sixty-six original reconnaissance reaches, seven were eliminated prior to analysis because the presence of large jams or a high level of woody debris loading had an overriding influence on channel form, slope, and particle size. Initially, cluster analysis was used to group the reaches into three classes -- constrained, unconstrained, and widely unconstrained, with 31, 26, and 2 cases falling into each class, respectively. Discriminant function analysis was then used to determine (1) the degree of overlap between classes and (2) variables most useful for discrimination. ANOVA was used on the remaining variables to determine the range of values in each class and degree of significance.

The results of the discriminant function analysis showed that channel type could be classified using a number of parameters measured in the field. Six variables were used including slope, valley floor width/bankfull width ratio, relative roughness (d/D_{84}), presence or absence of step-pools,

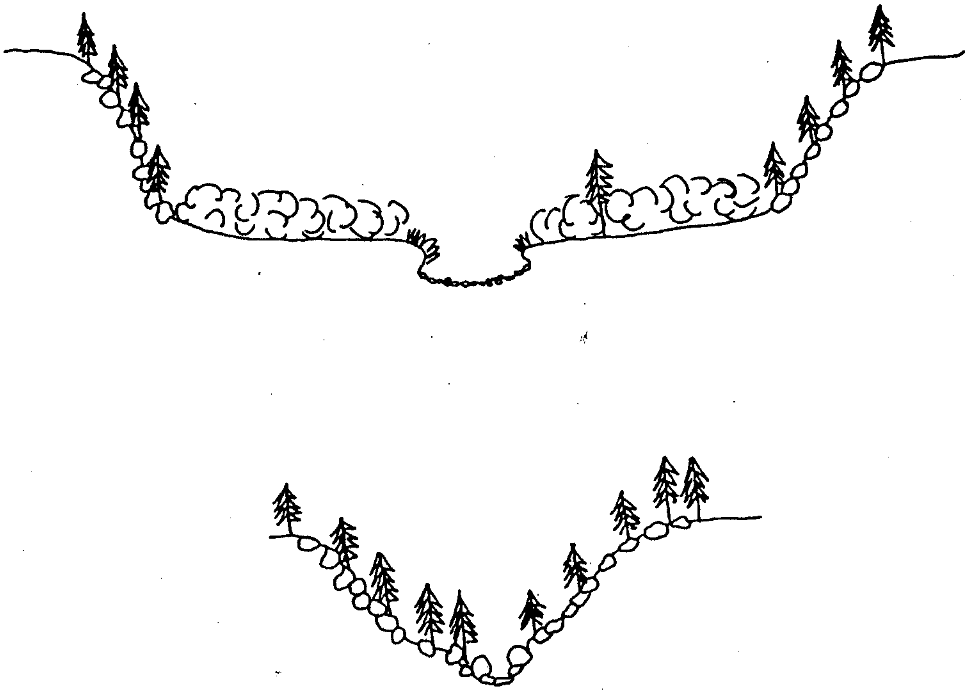


Figure 7. Cartoon of constrained and unconstrained valley bottoms, showing relative differences in width between valley walls, vegetation, and bed particle size.

riparian vegetation class, and number of boulders. Two statistically significant discriminant functions were derived with the first factor having a canonical correlation of 0.92 and the second with 0.62. Figure 8 is a plot of canonical values plotted in discriminant space. The valley floor width/bankfull width ratio proved most useful in classification with minimal overlap between constrained, unconstrained, and highly unconstrained channel types; factor 1 is dominated by the effects of this variable. Presence or absence of step-pools, riparian vegetation class, and channel slope were also useful for classification purposes, though more overlap was apparent. The discriminant functions distinguished all 59 sites in the same way as the field classification.

The degree of significance of the non-overlapping classification based on factor 1 suggests that the distinction between channel types tends to be more of a "threshold" (Schumm, 1973) rather than a "transition". That is, the channels in the subalpine region are either tightly constrained, steep, step-pool systems or unconstrained, moderately steep, pool-riffle (or rapid) systems. The distinction between the two tends to be sharp, with the cutoff occurring where the valley floor is six times the active width of the channel. This is not to say that transitional reaches do not occur, but rather they are less common and frequently have other influencing factors, such as woody debris accumulations.

The sharp distinction between constrained and unconstrained channel types indicates the overwhelming control of the valley floor characteristics on channel morphology. TABLE II lists the mean, standard deviation, standard error, and significance at the $\alpha = 0.01$ level for a number of characteristics; all were significant at this level. The two sites that fell into the highly unconstrained classification were grouped with the unconstrained sites for the purposes of this analysis, since so few were sampled. The effects of woody debris on this relationship have yet to be addressed fully, though it appears sites with high wood loads tend to accumulate finer particles and exhibit pool-riffle topography typical of unconstrained channels, while the valley floor width/bankfull width ratio may classify it as constrained.

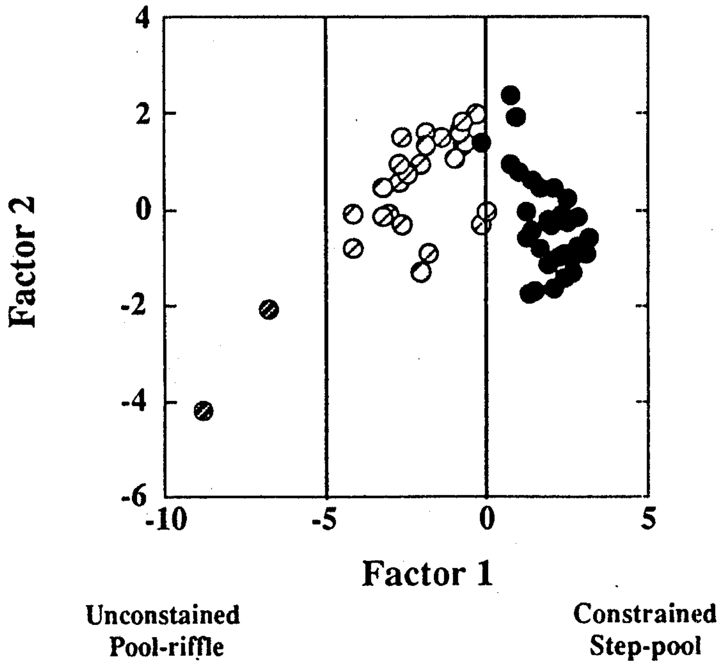


Figure 8. Plot of discriminant function analysis using channel and valley floor parameters. Based 57 cases -- sites with high woody debris load excluded, as explained in text.

Table II. Parameters Measured in Constrained and Unconstrained Channels

Parameter	Constrained/ Unconstrained	Mean	Standard Deviation	Standard Error
Water Surface Slope	C	0.048	0.027	0.005
	UC	0.014	0.006	0.001
Valley Floor Width/ Bankfull Width	C	4.40	1.55	0.28
	UC	13.30	5.61	1.06
Estimate Supercritical Flow (% area)	C	41.3	14.8	2.8
	UC	18.2	8.6	1.6
Roughness d/D84	C	1.23	0.53	0.10
	UC	2.19	0.93	0.18
Manning's *n*	C	0.081	0.030	0.005
	UC	0.032	0.013	0.002
Riparian Vegetation Class (1)	C	6.6	1.2	0.216
	UC	4.7	0.9	0.184
Boulders per square meter	C	0.24	0.21	0.03
	UC	0.05	0.10	0.02
Step-Pool Presence (2)	C	1.2	0.3	0.06
	UC	1.9	0.2	0.03

(1) Riparian Vegetation Class - Based on percent basal area covered by trees, shrubs, and grasses.
1-2 primarily grass and shrubs, 3-4 shrubs and few trees, 5-6 small trees and shrubs,
7-8 subalpine forest.

(2) Step-Pool Presence - 1 Well developed step-pools, 1.5 Poorly developed step-pools,
2 no step-pools.

In short, topography and flow hydraulics differ significantly between channel types. Intuitively, the rates and timing of sediment transport should vary as well and are examined more fully in the next section on bedload transport. A preliminary consideration using the dimensionless shear stress (τ_*) at bankfull flow for constrained and unconstrained sites is presented here. There are inherent difficulties in estimating an average τ_*, for gravel bed streams, such as errors associated with defining a suitable depth (Andrews, 1983; Bathurst and others, 1987) and adequately determining the distribution of particle sizes (Fripp and Diplas, 1993). Current methods tend to overestimate available shear stress in high gradient streams as the hydraulic roughness, commonly estimated by one representative particle size, is difficult to characterize and fails to account for the range of particles in non-uniform bed material and the degree of packing between them (Whiting and Dietrich, 1990). As such, the values calculated here provide only a rough guide for estimating the average forces at the bankfull stage.

τ_*, a measure of the fluid forces tending to initiate transport over the forces tending to keep the bed at rest, was calculating from reconnaissance data using:

$$\tau^*_{50} = \frac{DS}{\left(\frac{\gamma_s}{\gamma_w} - 1\right) d_{50}} \tag{2}$$

where D is the average depth at bankfull stage, S is water surface slope measured over the study reach, γ_s is the specific weight of sediment derived from granitic sources (25,970 N/m^3 used here), γ_w is the specific weight of water (9800 N/m^3), and d_{50} is the median particle size of the bed surface derived from pebble counts. The average bankfull τ_*, was 0.080 ± 0.042 in constrained reaches and 0.036 ± 0.016 in unconstrained reaches; the difference is significant at the $\alpha = 0.05$ level. Greater τ_*, in constrained channels suggests they withstand greater shearing force before transport occurs than unconstrained reaches. However, the bed at constrained sites remains largely stable at bankfull discharges as the large cobbles and boulders form a protective lag deposit and much of the available shear stress is lost due to spill and form resistance from large roughness elements (Bathurst, 1982). So while the potential for high transport exists in constrained channels, hydraulic conditions and coarse-beds limit the transport capacity. Constrained channels are comparable to "threshold" channels, defined by Lane (1953) and later by Andrews (1984) for Colorado streams, where the channel bed is mobile only at the highest flows. Unconstrained channels are comparable to "quasi-equilibrium" channels where bed material of all sizes are moved on a relatively frequent basis -- on the order of several times a year (Andrews, 1984). Bedload transport data from St. Louis Creek, described in the next section, confirm such differences in mobility between constrained and unconstrained sites, even under less than critical conditions.

4.3 Discharge and Sediment Transport at St. Louis Creek

Bedload transport relationships are particularly difficult to define and predict for mountain streams, as reflected in the number of equations derived to estimate initiation and transport of large-caliber material (Meyer-Peter and Muller, 1948; Einstein, 1950; Yalin, 1963; Bagnold, 1980; Parker and others, 1982). Incipient particle motion is influenced by many factors including the interaction between heterogeneous particle sizes (Parker and others, 1982; Kirchner and others, 1990; Wilcox and McArdell, 1993) and presence of large-scale bed topography (Reid and Frostick, 1984; Brayshaw, 1985; Bathurst and others, 1987). The distribution of bed particles is commonly bimodal (Thoms, 1992; Wilcox, 1993) with large particles hiding smaller particles from the influence of the flow. This tends to equalize the mobility as the larger particles, being more exposed to the flow, move at less than predicted shear stresses while smaller particles are released into the flow only when larger particles are moved (Parker and Klingeman, 1982; Parker and others 1982, Andrews and Parker, 1987). The entire bed tends to move as a unit (Parker and Klingeman, 1982; Andrews, 1983; Reid and Frostick, 1984) with minimal transport occurring until the threshold condition is reached or exceeded. The effects of hiding and packing on the prediction of incipient particle motion are reduced by using a measure of the larger particles the channel bed in bedload transport equations (Andrews, 1983). Representative particle size is determined using an average of the largest rocks moved (Costa, 1983) or a high percentile from a percent-finer-than cumulative frequency curve of the bed material (i.e. D_{50}, D_{84}, D_{95}).

Though a tendency toward equal mobility is exhibited by many gravel-bed streams (Wilcox, 1988), incipient particle motion is rarely a direct function of stream discharge. Intuitively, bedload transport is related to changing shear stress, discharge, or stream power, but there is poor correlation between predicted and measured bedload transport rates (Reid and Frostick, 1984; Reid and others, 1985). Considerable fluctuations in the timing and rate of transport have been noted despite constant flow rates (Hayward, 1980; Ashida and others, 1981; Gomez and others, 1989); such fluctuations have been associated with episodic supply events. Others have noted a cyclic or pulse-like nature to sediment movement associated with the passage of bedforms (Reid and others, 1985; Whittaker, 1987; Gomez and others, 1989). There may also be a seasonal or "event" component where a short period of intense transport occurs with on the rising limb of the hydrograph followed by a long period of minimal transport, despite increasing or constant flow rates (Reid and Frostick, 1986).

Bedload transport and velocity were measured over the peak flow season in 1992 primarily to document differences in the rate and timing of sediment movement between diverted and free-flowing channel segments. Constrained and unconstrained sites were included in the sampling scheme to evaluate the effect of different bed structures on the release of particles to the flow and to examine some of the theoretical considerations described above. TABLE III lists characteristic channel morphology, bed topography, and flow hydraulics for each site. Briefly, sites 1 through 3 are diverted (D), sites 4 and 5 are free flowing (FF), sites 1 and 5 are constrained (C), and sites 2, 3, and 4 are unconstrained (UC).

4.3.1 Discharge Measurements During Peak Flow

Regionally, the spring of 1992 was unusually warm and seasonal runoff began in May on St. Louis Creek, rather than late May to early June typical of most years. Sampling was underway by

Table III. Channel Morphology, Bed Topography, and Hydraulic Charateristics of Five Sites on St. Louis Creek,1992.

Site #	Bed Topography	Valley Floor Type	Flow Management	Vegetation Type	Greatest Measured Width (m)	Water Surface Slope	Greatest Avg Depth d (m)	D95 Particle Size (mm)	Median Particle Size (mm)	Relative Roughness d/D84	Highest Measured Velocity m/s
1	Step-Pool	Constrained	Diverted	Forest	7.25	0.040	0.34	361	127.55	0.94	1.04
2	Riffle	Unconstrained	Diverted	Willow, Herbs	7.15	0.020	0.35	172	75.88	2.03	1.13
3	Riffle	Unconstrained	Diverted	Willow, Herbs	8.30	0.019	0.31	181	81.93	1.71	0.91
4	Riffle	Unconstrained	Free-Flowing	Willow, Herbs	6.60	0.024	0.35	199	123.93	1.76	1.07
5	Step-Pool	Constrained	Free-Flowing	Forest	5.30	0.045	0.33	437	160.56	0.76	0.91

the third week in May to accommodate this early rise. Within days, several inches of new snow fell in the Fraser alpine and temperatures dropped below freezing, temporarily halting the discharge of meltwaters to the stream. This caused the drop in discharge measured at free-flowing sites between days 143 and 154 plotted on Figure 9b. Sampling was conducted through this period, though the discharges were low and minimal sediment was collected.

Unfortunately for the purposes of this study, diversion was slight during the peak flow between days 160 to 177. The Moffat diversion system, of which St. Louis Creek is part, was essentially shut down during this period to allow repairs to Gross Reservoir on the east side of the continental divide. On day 159 flow was released from two tributaries from which all water is normally diverted. By day 162, flow spilled over the diversion dam on the main stem and nearly all available water was released to the natural channel. As a result, discharge at diverted sites was often greater than at free-flowing sites, at least during the period of flow release (Figures 9a and 9b). After day 170, diversion patterns were sporadic and with some portion of the tributary flows removed on a continuous basis.

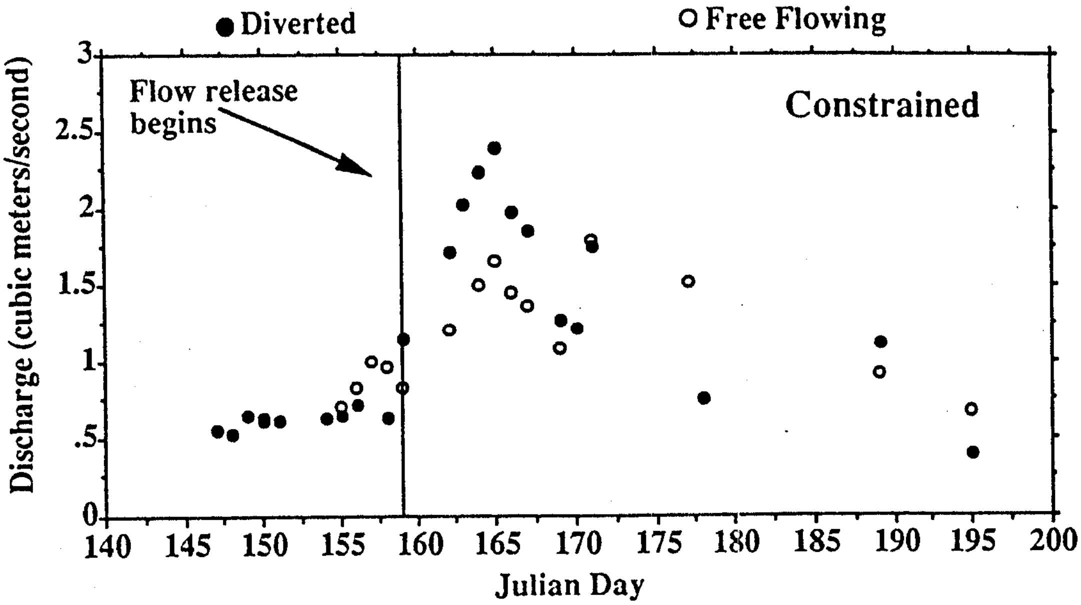
4.3.2 Transport Rates at Five Sites

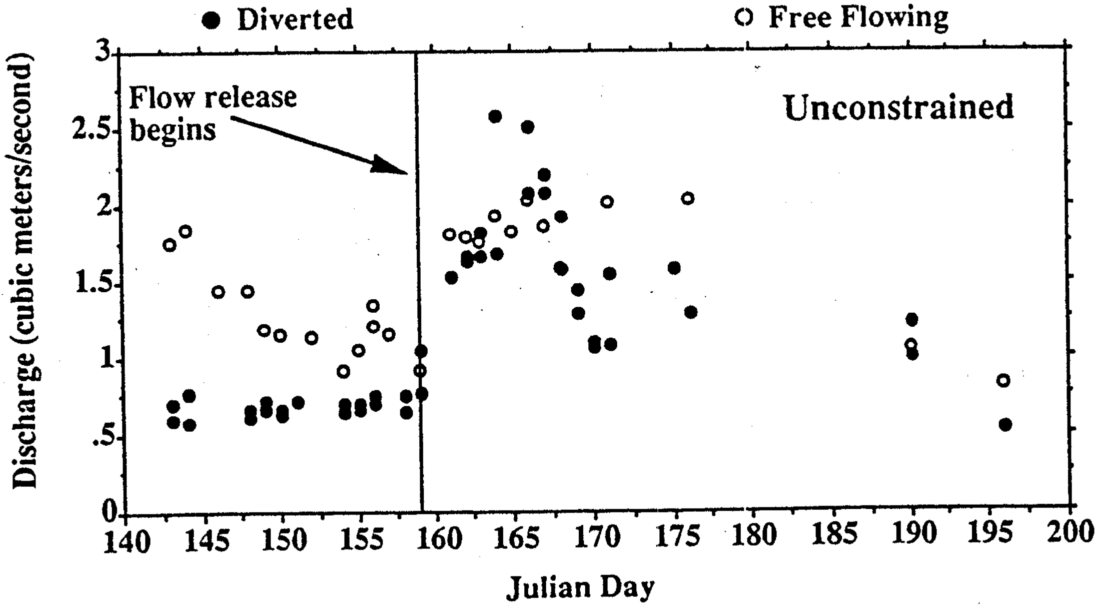
Unit bedload transport rates (kg m^{-1} s^{-1})were calculated using:

$$I_b = G/(wnt) \qquad (3)$$

where: G is total weight of composite sample (kg)
w = width of the Helley-Smith sampler (m)
n = the number of verticals
t = time sampler was held in place (seconds)

Bedload discharge was calculated by multiplying the unit bedload transport rates by the wetted channel width.





Figures 9a and b. Discharge measured at constrained (a) and unconstrained (b) sites during bedload transport study. Flow released from main diversion dam on day 159 (June 7); peak flows measured on day 165 (June 13).

Essentially, a seven to ten day window of transport was observed in both the diverted and free flowing segments (Figure 10). Transport rates remained low in the early part of the study, despite an initial rise in discharge in the free flowing segment in late May. Both flow and sediment discharge increased around day 163, a trend which continued though the peak on days 165 and 166. Transport dropped off within a few days after the peak and was negligible after day 169, though discharges remained higher though day 177. By day 195 transport had nearly subsided and sampling was discontinued.

4.3.3 Comparison of Transport Rates at Diverted and Free-flowing Sites

The hypothesis that unit bedload transport rates in diverted sites are significantly less than free-flowing sites was tested using analysis of variance (ANOVA). The results showed no significant difference in the *average* transport rates between any of the sites, while the *highest* transport rates were partially commensurate with greater discharge occurring in the diverted segments after flow release (Figure 11). The highest transport rates at site 1 (D) were significantly greater than those at site 5 (FF) where peak flows were 1/3 less (2.40 vs 1.65 $m^3 s^{-1}$) ($\alpha = 0.05$). The highest transport rates at 2 (D) were significantly greater than site 4 (FF), though there were no differences between sites 3 (D) and 4 (FF) ($\alpha = 0.05$); again, slightly higher flow at site 2 probably accounts for increased transport (~2.50 at site 2 vs ~ 2.10 $m^3 s^{-1}$ at sites 3 and 4). Differences in flow between sites 2 and 3, which are only ~150 m apart, was due to sampling later in the day at site 2.

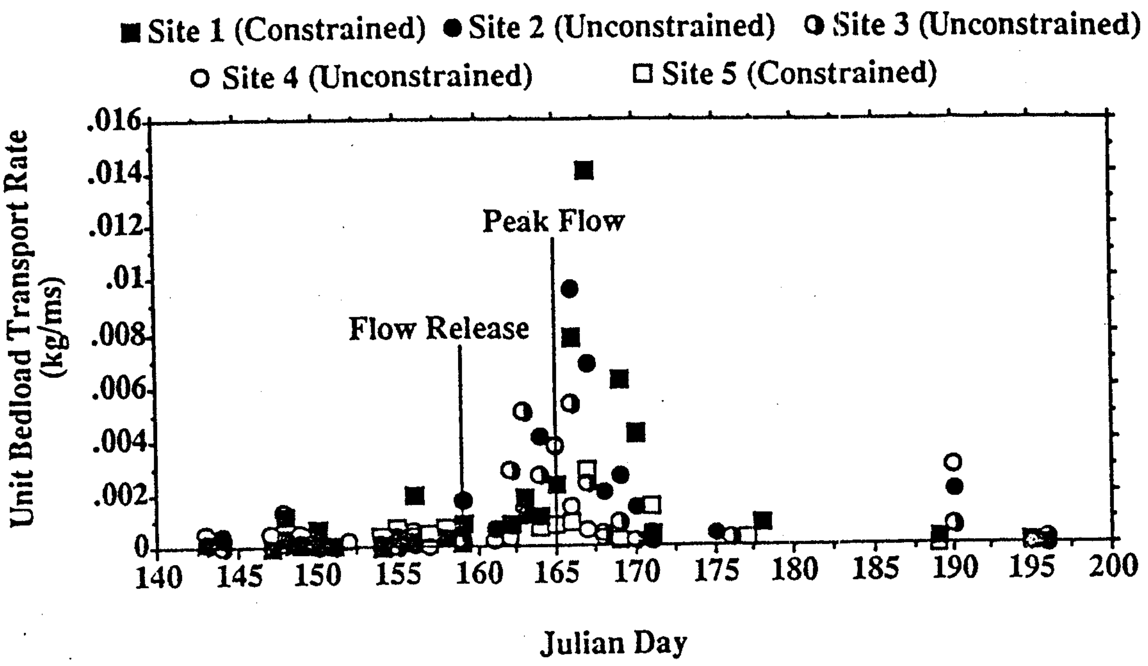


Figure 10. Timing of unit bedload transport rates measured at all sites relative to flow release and peak flow. Ten day window of increased transport noted, despite changing flows as depicted on Figures 9a and b.

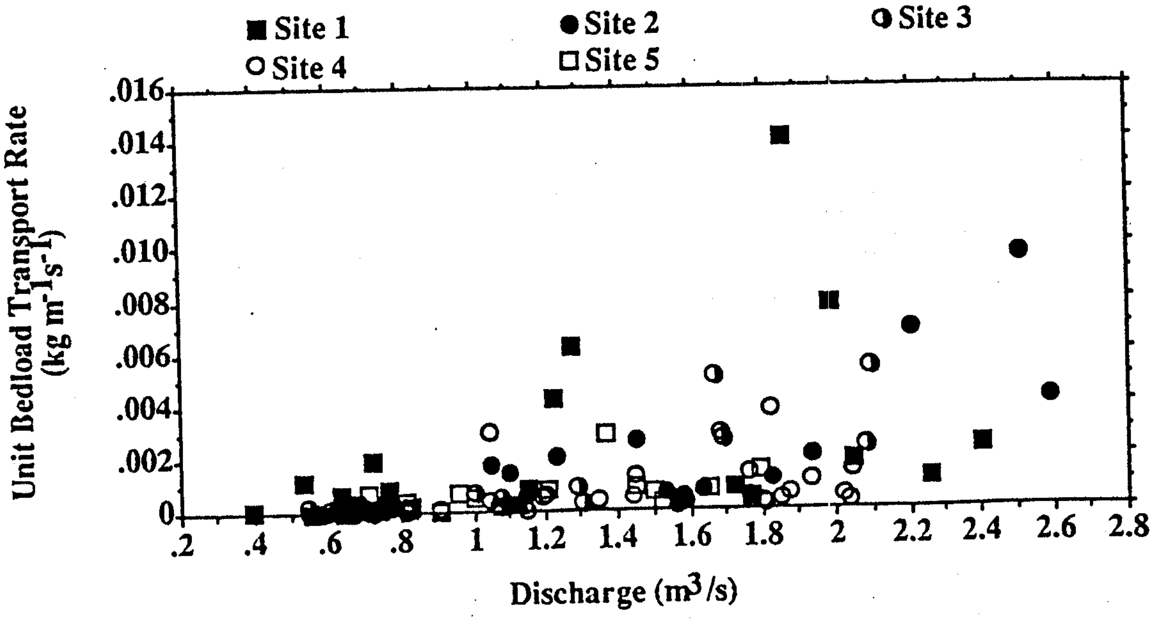


Figure 11. Unit bedload transport rates and discharge measured at five sites. Peak transport rates were partially commensurate with increasing discharge, with greater discharge and transport rates measured at sites 1 and site 2. No significant difference in mean transport rates was evident between any of the sites.

The release of flow to diverted sites and the resulting higher transport rates were initially viewed as counter to the goals of this study. However, since 1992 was a relatively low flow year, the measured peak discharge was close to average for the diverted period and much lower than the unaltered period (Figure 12). Transport rates measured at sites 1, 2, and 3 are, therefore, typical of the diverted period, while the rates measured at 4 and 5, where peak flow was estimated to be 60 to 80 percent of bankfull, are probably low. So while direct comparison of diverted and free-flowing transport rates is not determinative, the total of the five records does provide insight into the interaction of streamflow and bedload during moderate or reduced flows. As much of the work on bedload transport in gravel and cobble bed streams focuses on critical or threshold conditions, an examination of transport characteristics under less than bankfull conditions is still relevant to the interpretation of diversion impacts on channel processes.

4.3.4 Comparison of Transport Characteristics of Constrained and Unconstrained Sites

In general, transport rates were similar for constrained and unconstrained sites, though peak unit transport rates were slightly higher for one of the constrained sites (between 0.008 and 0.014 kg $m^{-1}s^{-1}$) than the unconstrained sites (between 0.008 and 0.010 kg m^{-1} s^{-1}). The difference of the means was significant between sites 1 (C) and 3 (UC) at the $\alpha = 0.05$ level; the means of the transport rates between sites 1 (C) and 2 (UC) or sites 4 (UC) and 5 (C) were not significant.

There were, however, substantial differences in the *timing* of peak bedload movement between constrained and unconstrained sites (Figures 13a and b). The increase in transport occurred first at unconstrained sites, specifically at site 3, the most unconstrained site, on days 162 through 166, the rising limb of the hydrograph. The initial increase at sites 2 (UC) and 4 (UC) occurred on days 164 through 167, roughly coinciding with peak runoff. The initial increase in transport at constrained sites occurred on the falling limb between days 166 through 170. This pattern is indicative of a hysteresis effect whereby differences in transport rates on the rising and falling

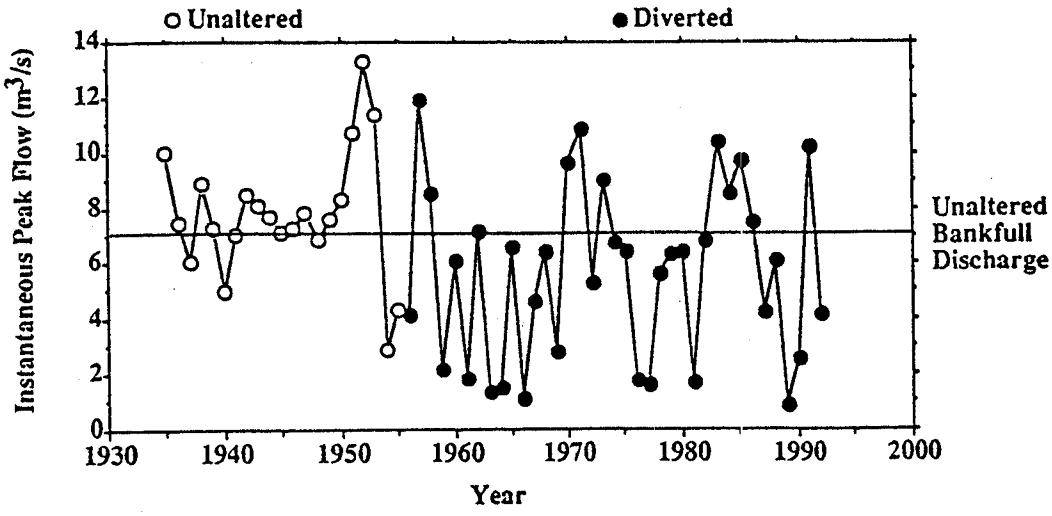


Figure 12. Instantaneous peak flows measured at USGS gage (09026500) between 1935 and 1992.

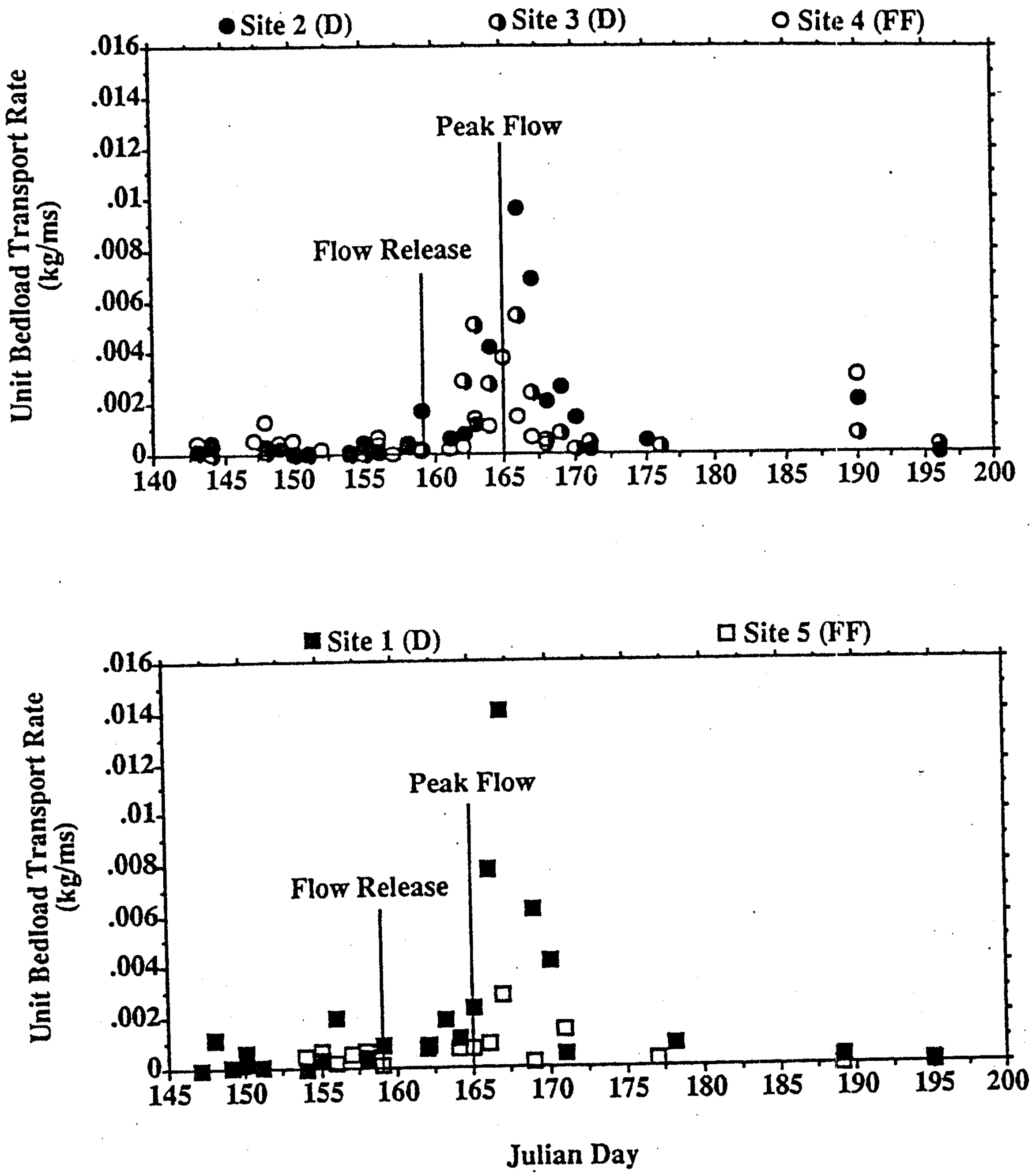


Figure 13a and b. Unit bedload transport rates measured at unconstrained (a) and constrained (b) sites. Note differences in initiation and cessation of transport between channel types, with initial transport occurring on the rising limb of the seasonal hydrograph at unconstrained sites and the falling limb at constrained sites.

limbs of the hydrograph can be attributed to changing sediment supplies. Transport on the rising limb suggests a more readily transportable sediment supply available in the channel prior to the event. Transport on the falling limb suggests a limitation on the availability of readily transported sediment or "sediment starvation". This effect has been noted in other studies of coarse material transport (Reid and Frostick, 1984) and the delay in transport is attributed to the effect of tightly interlocking particles and numerous hiding spaces requiring forces much greater than the submerged weight of the particles to engage bed material. Once particles are entrained, though, less force is required to move along the bed surface, providing one possible explanation for pulses of sediment movement on the recessional limb of the event observed here.

4.3.5 Critical Dimensionless Shear Stress Estimates for Five Sites

Defining conditions under which gravels and cobbles, the size classes dominating the bed surface area, are moved is a particularly onerous task. High flows required to initiate transport are usually deep, turbulent, and turbid, preventing direct physical or visual observation of bed motion. Bedload movement is commonly sampled using a variety of hand-held and stationary traps and samplers. Average flow conditions, such as discharge, stream power, and shear stress measured at the time of particle capture, are *presumed* to be the critical conditions at which motion began, with the largest particles trapped representing flow competence. However, the conditions measured at the point of capture are may not be the same as those at which the particles were entrained, making such presumptions suspect.

Dimensionless shear stresses are used here instead of discharge or stream power as they relate forces imposed on the bed with a measure of bed resistance, providing a better sense of geomorphic relationships involved. Typical values reported for the threshold dimensionless shear stress ($\tau_{*,cr}$) for channels with large particles and high Reynolds numbers, typical of mountain streams, range from single values of 0.020 (Andrews, 1983) to 0.047 (Meyer-Peter and Muller, 1948), to 0.060 (Shields, 1936), to 0.10 and greater (Bathurst and others, 1987). Williams

(1983) found the $\tau_{*,cr}$ for an individual particle diameter could range from 0.01 to 0.25, based on data from a number of published reports. The wide range of values is attributed primarily to variation in particle size and bed conditions, though differences in methods of observation and problems of defining the precise moment of motion also complicates the relationships. Clearly, no single value is appropriate for predicting bedload movement for the full range of rough channels encountered.

In this study, the point at which larger particles began to move was used to approximate the threshold of motion ($\tau_{*,cr}$)for the five sampling sites (similar to Andrews, 1983). τ_{*}, was calculated for all samples with grain-size fractions > 10 mm (medium gravels and larger) using equation (2) given earlier then plotted against the D_{95} of the bedload sample (Figure 14). In this case, D was the average depth of the verticals, S was the water surface slope measured over the entire study reach during low flow, and d_{50} was the median particle size of the bed. The resulting τ_{*}, is mainly a reflection of changing flow depth at a site as slope and roughness values remained the same. A constant value for flow resistance is justified as Andrews and Erman (1986) have shown that the particle distribution of the bed of gravelly streams changes little during a flow event; it is, therefore, reasonable to assume d_{50} remained constant, especially at the moderate flows measured here. Though water surface slope also changes with discharge, a constant value which approximates the slope of the energy gradient and channel or valley floor was used as the the three are presumably parallel in uniform flow (Richards, 1982) and approach the longitudinal slope as measured from topographic maps during peak events (Wolman, 1955).

Several features of the pattern of gravel movement at moderate flow are evident on Figure 14, specifically: (1) the size of the largest particles sampled, (2) the sites where coarse material was collected, and (3) the flow conditions under which coarse particles were trapped. In general, some gravels were in transport under the full range of conditions as particles between 10 and 22 mm were collected at all sites at τ_{*}, ranging from 0.025 to 0.065. Coarse gravel movement was more sporadic and not observed at τ_{*}, less than 0.035. Of the five samples with coarse gravels, three

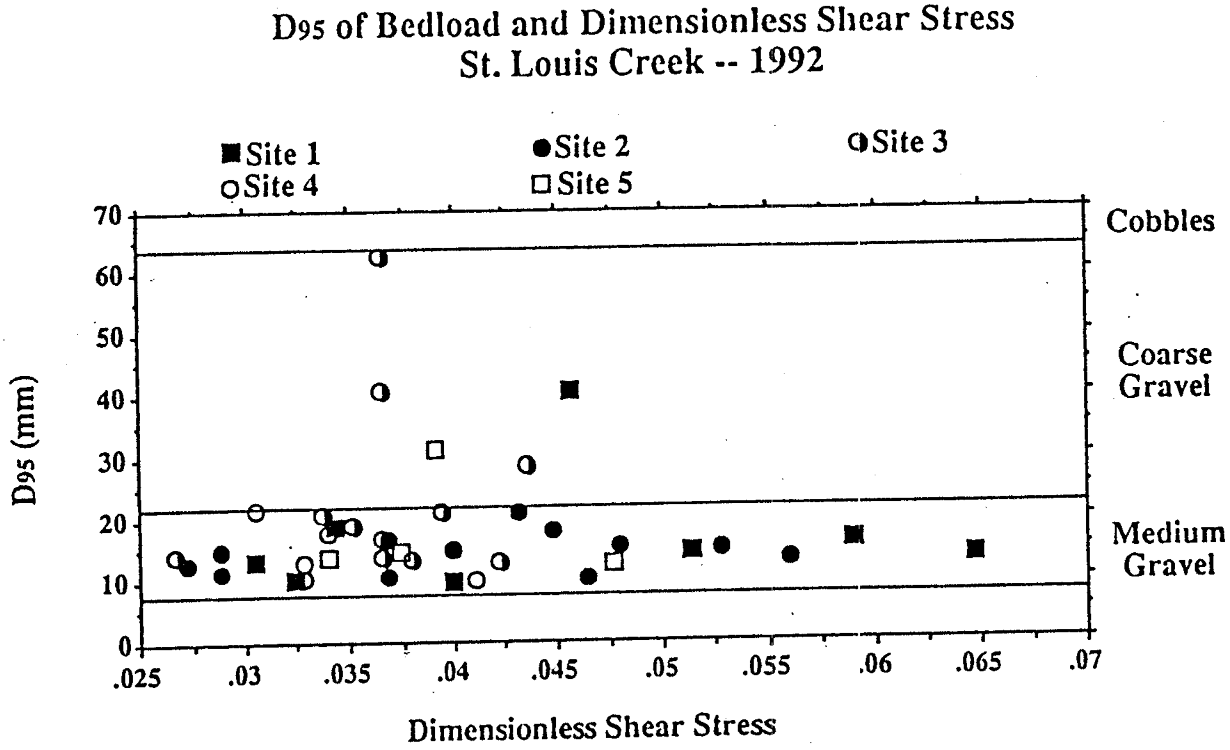


Figure 14. Comparison of coarsest fractions (> 10 mm) trapped and dimensionless shear stress. D_{95} is a measure of the largest particle in a sample (95th percentile on a percent finer than scale).

were from site 3 (UC) and two were from sites 1 (C) and 5 (C). Since several samples contained coarse gravels, it is reasonable to assume at least partial mobility at site 3 where 40% of the bed is composed of particles less than 64 mm; a τ_{*cr} of about 0.040 seems appropriate for approximating the point at which partial bed mobilization occurs. Less can be concluded about $\tau_{*,cr}$ at constrained sites as only 2 samples included coarse gravel, material much finer than the cobbles and boulders on the bed. Additionally, no coarse gravel was trapped at τ_*, approaching 0.06 and 0.07 at sites 1, 2, and 5, indicating the minimum τ_*, required to transport such particles was probably not achieved.

No cobbles were collected in any of the samples, suggesting that particles comprising much of the armour layer remained stable. However, the absence of cobbles could be due to size limitations of the sampler rather than an absence of movement. Painted rock studies were used to corroborate the Helley-Smith data to determine whether larger material was in motion but simply unable to fit in the sampler. Rock movement shown in a sequence of a photographs of painted portions of exposed gravel bars at unconstrained sites indicates that small-to-coarse gravels were in motion, though the armour was not broken up (Figures 15 and 16). Particles that moved onto the painted area were essentially the same size as those moved off and of the same size trapped in the sampler; cobbles remained stable. Similar sequences taken at constrained sites also show cobbles remained stable and armour remained intact (Figure 17). Some fines, indicative of a passing over of sand and small gravel, infiltrated between cobbles. These photographs confirm the earlier findings that the coarse portion of the bed remained stable and primarily sands and small gravels were transported under the moderate flow event.

4.3.6 Summary of Transport Characteristics at Moderate or Reduced Peak Flows

This analysis used unit bedload transport rates and particle size analysis to assess characteristics of transport in coarse grained channels under a moderate runoff event. Samples from the five sites were strikingly similar in volume and content, containing primarily sands and

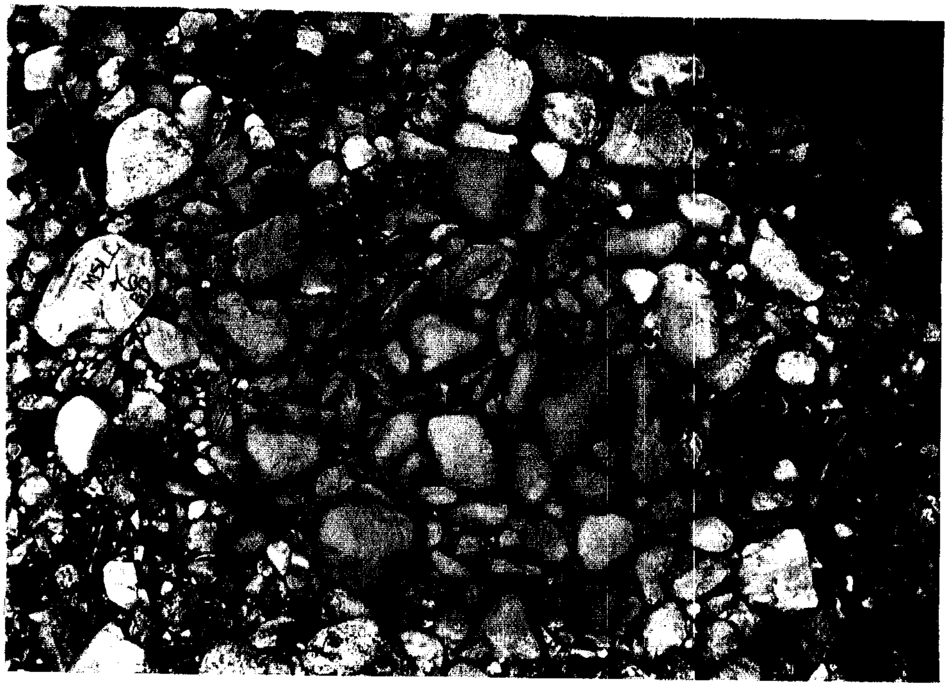


Figure 15a. Photograph of painted circle (1' in diameter) on exposed gravel bar at unconstrained site before peak flow in 1992. Particle size primarily medium gravel. Note disturbance of armour layer prior to event.

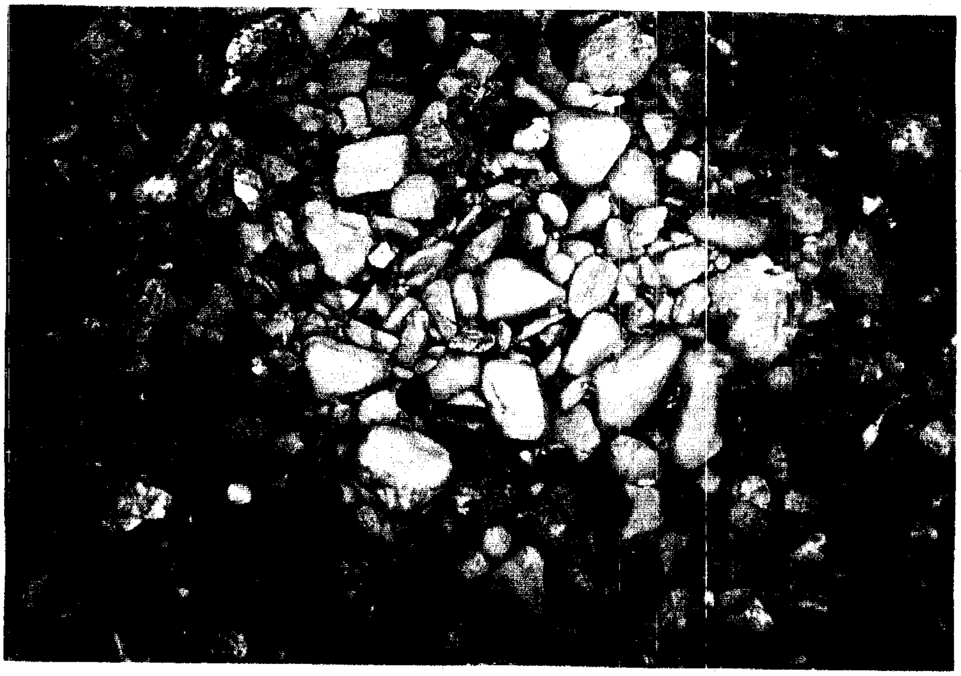


Figure 15b. Photograph of painted circle on exposed gravel bar at unconstrained site after peak flow. Particles moving on and off painted area are of similar size. Note armour layer is re-established by particles from outside the painted region.

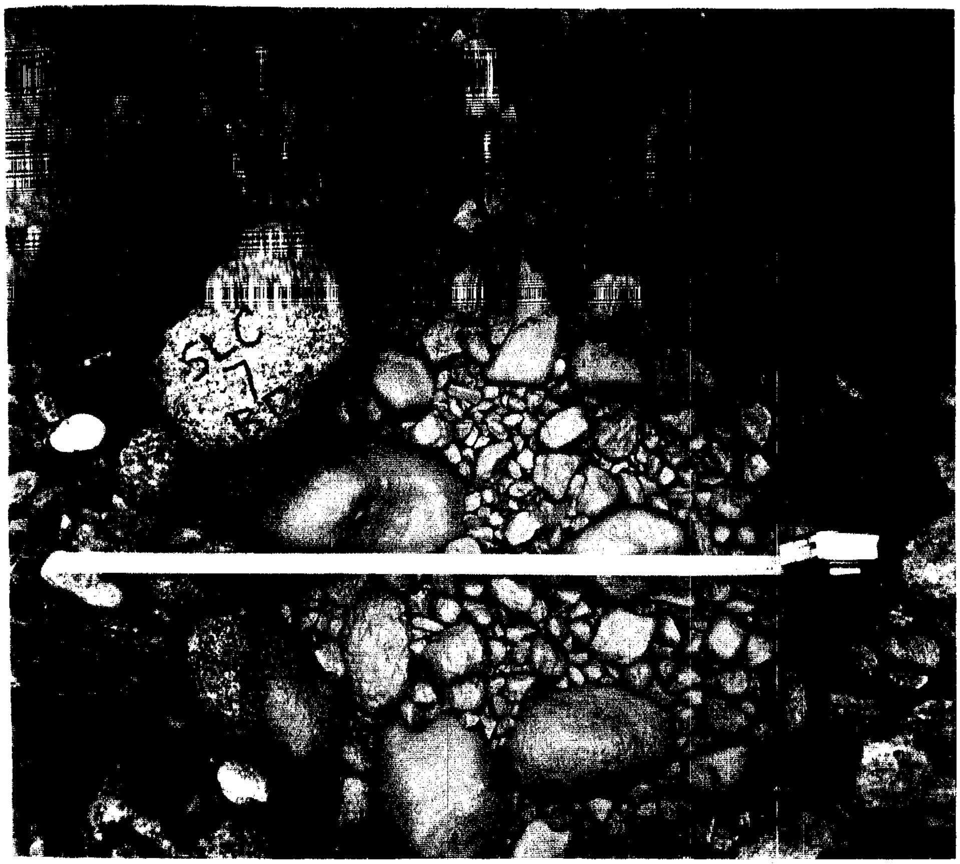


Figure 16 a. Photograph of painted circle (1' in diameter) on exposed gravel bar at unconstrained site before peak flow in 1992. Particle size is medium gravels to small cobbles.

Figure 16 b. Photograph of painted circle (1' in diameter) on exposed gravel bar at unconstrained site after peak flow. Particles moving on and off circle are primarily medium gravels; cobbles

Figure 17 a. Photograph of painted circle (1' in diameter) on exposed channel surface at constrained site after peak flow in 1992. Particles are primarily cobbles with few small gravels.

Figure 17 b. Photograph of painted circle (1' in diameter) on exposed channel surface at constrained site after peak flow. Cobbles remained in place with some sand infiltration.

small to medium sized gravels. Absence of larger particles suggests that much of the coarse material remained immobile during the event and that fines simply passed over a stable bed. However, one site appeared to be slightly more "mobile" than the others. Site 3 is the most unconstrained site, with active gravel bars and a relatively "loose" bed (in the sense of Church, 1978); coarse material approaching the median bed particle size was trapped in the sampler on several occasions. By comparison, sites 2 and 4, though also unconstrained, have slightly coarser beds and tighter imbrication which restricts particle motion and requires higher shear stresses to dislodge; as a result, no coarse gravels were trapped at sites 2 and 4. Hence, slight differences in channel characteristics influence the release of particles to the flow even within a given "channel type".

Conversely, though the greatest transport rates were measured at a constrained site (1), the bed of the constrained sites remained largely stable. It is suggested that particles trapped may have originated either from unconstrained reaches upstream or from temporary storage sites within constrained reaches and not from the local bed. This is based on the following evidence: (1) the bedload was much finer than the bed, (2) movement occurred in pulses after the peak flow, and (3) based on painted rock stability, the bed surface largely undisturbed. Additionally, most of the sediment trapped in the constrained reaches came form one or two verticals, notably in absence of large boulders directly upstream; there was no correlation between depth or shear stress at a vertical and transport rates (Figure 18). Travel distance estimates from Schmidt and Ergenzinger (1992) confirm the possibility of material entrained in unconstrained sites during the early part of runoff reaching and moving through constrained sites during the latter part of the runoff season. Similar observations of intense transport of fines through steep channels, with larger particles remaining immobile, have been made by Bathurst and others (1987) and Carling (1983), among others.

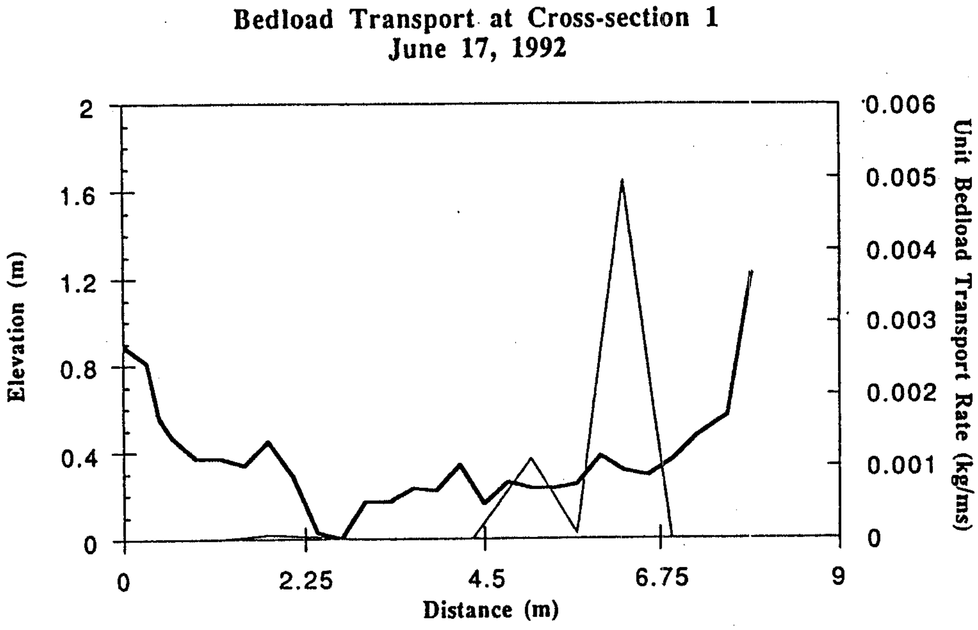


Figure 18. Bedload transport rates separated by vertical at site 1. Measured on June 17, 1992, slightly after peak flow. Dark line represents bed topography, thin line represents unit bedload transport rates.

Such differences in bedload mobility will influence the ability of a channel to respond to reduced flow regime. Change in form requires redistribution of bed material, so some transport is needed for change to be apparent. In streams with very coarse bed material, the wide distribution of particle sizes and structure of the bed topography stabilize the channel perimeter. The whole bed is probably in motion only during extreme events, when larger sediment is mobilized and particles of all size fractions are moved by the flow (Bathurst and others, 1987). Hence, flow reduction has little influence in changing channel form, at least at the time scales considered here, as channel surfaces remain immobile. Unconstrained sites, with smaller particles, "looser" beds, and absence of stepped structure, are apparently more mobile, as evidenced by some coarse sediment transport even at moderate discharge. Additionally, gravel bars, limited to unconstrained channels, are both a source of transportable sediment and the first sites affected by a reduced regime as they are reworked and mobilized only during flooding. Changes in channel form are expected where bars are no longer inundated and vegetation invades and stabilizes the formerly mobile surface. It is therefore hypothesized that impacts will be more apparent in unconstrained channels as *they are partially mobile even under reduced flows*, providing a mechanism for changes in bed topography and channel morphology.

4.4 Effects of Flow Diversion on Channel Width

A fundamental concept in fluvial geomorphology is that the size of a stream channel is a function of some combination of flow frequency and magnitude. Changes in morphology should occur where long-term changes in the flow regime, either from natural or anthropogenic influences, have been imposed. There are, however, a number of opinions as to whether steepland channels are formed and maintained under the current flows and, hence, able to alter their form. Miller (1958) concluded that beds of mountain streams in New Mexico were highly stable and that movement of particles in a step-pool system would require changes in the hydraulic regime characteristic of glaciation or deglaciation. Another, perhaps more common, viewpoint is that high gradient channels are formed during high magnitude, low frequency events, such as large floods or debris flows (Stewart and LaMarche, 1967); recent work proposes a 25-50 year return interval for such events (Hayward, 1980; Best and Keller, 1986; Grant and others, 1990). Others have suggested that shear stresses at bankfull discharge, achieved several times a year, are just sufficient to entrain bed material of all sizes and are active in channel maintenance (Pickup and Warner, 1976; Andrews, 1984).

This diversity of opinions may be related to regional differences in physical processes. In areas with large floods or debris flows, channels tend to retain the imprint of large-scale events (Baker, 1977; Grant and others, 1990; Benda, 1990). In areas where peak discharges have low variability, such as snowmelt regimes where floods produced by intense rainfall or rain-on-snow events are rare (Jarrett, 1990), channels may reflect events which occur on an annual basis. It is, therefore, expected that streams in this study should show some reduction in channel capacity if the channels are in "equilibrium" with the former annual event. However, given the relatively low bedload transport rates common to subalpine systems (Andrews, 1983) and the relative stability of channel banks and surfaces, the changes may be subtle and take decades to become evident.

Many studies have documented changes in channel form and have linked them, directly or indirectly, to anthropogenic influences. Fortuitous finds, such as surveys and photographs recording channel dimensions prior to diversion, are particularly useful for documentation, but, unfortunately, were not available for the sites considered here. Aerial photographs taken prior to diversion were either too coarse in resolution to identify channel structure or the view of the channel was obscured by forest canopy. In this analysis, channel response was assessed primarily by examining spatial and temporal differences in cross-sectional features and linking them to changes in discharge resulting from diversion. An initial broadscale attempt to document such changes compared surveys of diverted channels with their respective free flowing segments. The length of time required for channels to respond to reduced flows was to be estimated by measuring channels with diversion histories that ranged in age from 20 to 100 years. However, the results proved inconclusive as the parameters, such as differences in particle size and cross-sectional area, fell within the predictable error range, indicating that either the methods were unsuitable for detecting subtle changes in channel form or that the channels showed no response.

A second, more detailed survey was conducted on St. Louis Creek using several measures of channel width representative of different flow levels. Changing channel width has been used as a as a relatively sensitive indicator of geomorphic response and recovery (Lyons and Beschta, 1983; Eschner and others, 1983; Ryan and Grant, 1991). While flow depth, bed particle size, and slope may also show changes, channel width proved most readily identifiable and measurable in the field -- an important constraint when surveying features over several kilometers and potentially monitored regionally by aerial photography. Additionally, reductions in channel width would also indicate a loss of lateral aquatic habitat and complexity which has important implications for fish and macroinvertebrate populations (Moore and Gregory, 1988).

Two widths were used in this analysis: (1) the *cutbank* width or the distance between the banks cut into the valley floor and (2) the *active* width or the width of the channel surface occupied by recent peak flows. The cutbank width was consistently wider than the active width, forming the most significant break between the channel and the valley floor. Cutbanks, composed of fine silt, sand, and clay and stabilized by grassy mats and willows, may no longer be inundated by the current flows, especially in diverted sections, but are retained in the landscape for decades or centuries. The active width was determined either by direct observation during peak flow or estimated by the presence of a vegetation line or a break in slope cut into a gravel bar indicative a recent washing or entrainment of the gravels.

Cutbank widths and active channel widths were measured for each channel unit classified in the diverted and free-flowing segments. Measurements were taken at the top, middle, and bottom of each unit and averaged. An index was then calculated by dividing the average cutbank width by the average active width. A value close to 1 indicates the active flow completely inundates the distance between cutbanks and no change in width is evident. The index provides a measure of change, either from natural or anthropogenic influences, which is independent of the scale of the channel.

The index was calculated first for the free-flowing sites to determine the range of values from an unaltered segment (Figure 19). Note that most values were greater than 1, suggesting that even at unaltered sites the active channel doesn't completely fill the cutbank distance; most values were between 1.05 and 1.25 indicating a "loss" between 5 and 20%. This is expected as channels undergo changes in morphology without significant changes in regime. An example would be the lateral shift of a channel meander where the top of the inside gravel bar is no longer inundated as the channel moves away. In subalpine streams, such changes are typically slow, but do occur. In short, index values less than 1.25 are reasonable and expected under unaltered conditions. The few sites greater than 1.25 can be directly linked to debris jams where substantial aggradation and cutbank widening has occurred. Note that little difference in the index range exists between constrained and unconstrained sites.

The width index for the diverted segment shows a pattern different from the free-flowing segment (Figure 20). Below 1300 m the channel is a steep, step-pool system flowing in a constrained valley. Here, the index shows no discernable difference in the cutbank and active channel widths, indicating the entire channel bottom is inundated by the annual flood even when water is diverted. This is expected in constrained channels as the lateral surface area is limited and the bottoms are inundated nearly year round. Again, the few sites with an index greater than 1.25 are influenced by large woody debris jams.

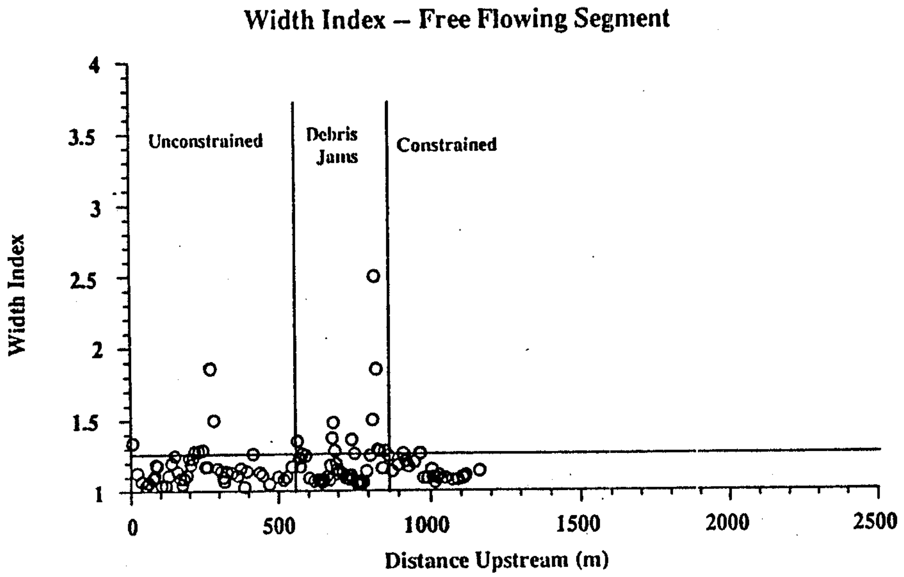


Figure 19. Width Index (cutbank width/active width) calculated for free-flowing segment, St. Louis Creek.

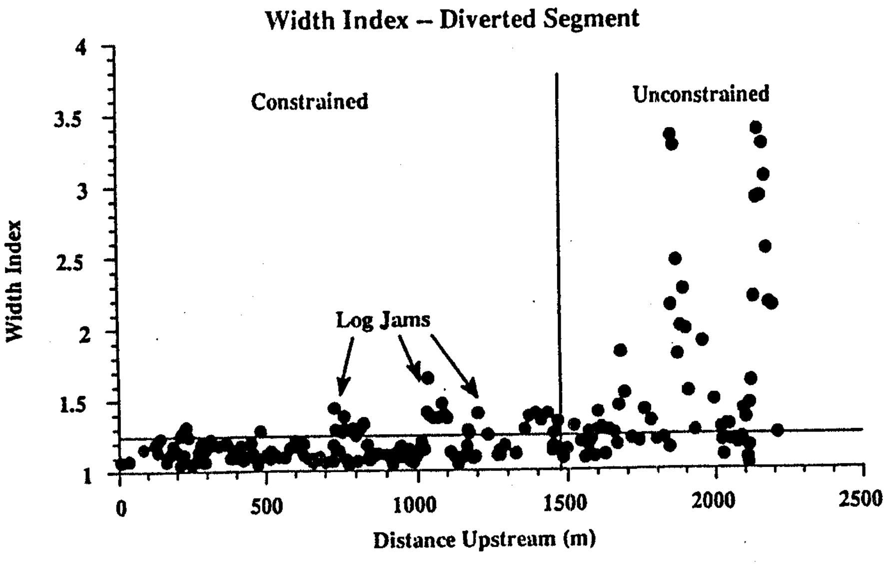


Figure 20. Width Index (cutbank width/active width) calculated for diverted segment, St. Louis Creek.

Between 1300 and 1500 m the valley bottom begins to widen and the channel takes on a more unconstrained character. Above 1500 m the stream meanders through a wide valley bottom and has a gentle gradient with pool-riffles and gravel bars. At this point the index increases substantially, indicating a much greater portion of the cutbank distance is no longer inundated and reworked by peak flows. Of the 78 channel units above 1300 meters, 47 (60%) have indices greater than 1.25. Of these units, the relative frequency is evenly split between riffles (32%), pools (30%), and rapids (25%); the remaining 13% are primarily log or boulder steps. Pools appear to have been impacted the greatest, with an average index of 2.11 ± 0.78. Rapids and riffles have average indices of 1.68 ± 0.51 and 1.54 ± 0.44, respectively. The pool indices were statistically significant from riffles at the $\alpha = 0.05$ level and from rapids at the $\alpha = 0.10$ level. The increase in the indices suggests there has been a considerable loss of channel area in pools, riffles, and rapids -- on the order of 35 to 50%. Note that while the sampling scheme was developed so the areas of constrained and unconstrained segments were similar, St. Louis Creek is largely unconstrained over much of its length below the diversion so the impacts are probably more widespread than appears here.

There are several mechanisms by which relatively stable channels adjust to reduced flow. Banks, no longer cutback and maintained by yearly high flows, slump into the channel, and become stabilized. Gravel bars are no longer overtopped and the edges may be cut back by reduced peak flows concentrated in the central portion of the channel. Vegetation, specifically grasses and willows, invade and stabilize portions of channel surfaces no longer reworked by seasonal high flow. In the diverted, unconstrained area of St. Louis Creek, continuous segments of a vegetated (herbaceous), low surface were evident beneath a former cut bank. The level of this lower surface was exactly coincident with the highest flow level of 1992, which, recalling Figure 12, was typical for a diverted peak flow. By comparison, cutbanks were maintained and, in many areas, actively cut back in the free-flowing section. Several of the low surfaces were excavated and found to consist of fine sand, silt, and clay over small to coarse gravels, typical of the sizes transported at reduced flow. It appears these surfaces are a low, composite bank formed in response to reduced flows.

Other changes may have occurred in St. Louis Creek , although without evidence from the unaltered period, these are difficult to prove. For example, changes in spacing of slope breaks may occur as pools and riffles adjust to reduced discharge and differences in transported bedload fractions transported. Flow depth may be decreased by aggradation and lower flows. Other potential impacts include a shift in the particle size distribution as sands and fine gravels wash into stable gravel and cobble beds. Tree invasion may occur on banks and floodplains as periodic flooding no longer damages and destroys young saplings colonizing these areas. There was, however, little evidence for particle fining and tree invasion in St. Louis Creek; apparently the stream receives enough flow on a frequent enough basis to offset such impacts. In particular, large events, such as 1983 and 1984 floods, have the potential to reset such changes by disturbing vegetation, washing fines from gravel and cobble beds, and restructuring channel topography. The timing of these events relative to the period of study could destroy much evidence. Additionally, evidence from smaller streams, such as Kings Creek on FEF, suggests that a complete dewatering of the channel over several years is necessary before trees are able to invade the channel surfaces at steep, constrained sites.

V. Summary and Conclusions

This study examined the morphological, sedimentological, and hydraulic characteristics of several stable, high-gradient, coarse grained channels in the Colorado Rocky Mountains, focussing primarily on diverted and free-flowing segments of St. Louis Creek on the Fraser Experimental Forest. All sites are located between 2700 and 3000 m in elevation in the subalpine ecotone where runoff is derived primarily from snowmelt and peak flow occurs most predictably in spring. The study focused on the interaction between water and sediment within the constraints of the varying boundary conditions or hydraulic and geomorphic controls. The specific objects were to assess: (1) how diversion alters flow regime; (2) whether quantifiable differences in initial boundary conditions exist between channels; (3) whether processes, including flow hydraulics and bedload transport, differ between channels with different boundary conditions; (4) whether rates and timing of bedload transport differ between diverted and undiverted channel segments; and (5) whether channels of varying initial boundary conditions respond differently to reduced flows.

Analysis of gage data from St. Louis Creek allowed detailed assessment of diversion impacts on several portions of the flow regime. In general, the average annual discharge at the USGS gage has been reduced by 45%, while the seasonal diversion yield has increased over the past 20 years. Greater impacts were evident during low flow years, resulting in an increase in flow variability. During drought, the channel is nearly depleted of flow in meeting claims while physical restrictions of the diversion system limits diversion yields during high runoff. The frequency of bankfull or critical flows were reduced from events occurring several days a year on average to ones that occur once in five to ten years. However, during this five-to-ten-year event a substantial amount of water may move through the channel as surplus flow is routed to the natural system. Potentially, these larger flows may reset structural changes effected in the channel during the prior period of low flows. Conversely, reduced channel capacity incurred during the dry periods may alter the ability of the channel to transmit flood waters.

Based on data from a reconnaissance survey of eight mountain streams, a classification was developed and study sites were grouped into one of two types. Channel morphology and, hence, flow hydraulics and relative mobility, were closely associated with the type of valley floor and the classification terminology reflects this relationship. To reiterate, constrained channels are tightly bound by the valley walls, have steep slopes (> 4 %), boulder beds, and a step-pool topography while unconstrained channels flow in wide valley bottoms, have more gentle slopes (1-2%), gravel and cobble beds and pool-riffle topography. The categories are necessarily broad for the purposes of this investigation as only a few channel types could be adequately assessed in the bedload transport study. Though the constrained/unconstrained distinction is, admittedly, a simplification of the subalpine system, it is useful for modelling larger-scale processes, such as sediment routing, in channels of varying morphology. Additionally, the classification compares favorably with others (e.g. Rosgen 1985) which break out more channel types based on additional parameters such as sinuosity and channel entrenchment. Rosgen's type "A" channel are essentially constrained channels and his type "B" channels are unconstrained. His type "C" (finer textured, low gradient, highly meandering) and "D" (coarse grained, braided) channels were not included in the survey of subalpine streams.

Bedload transport measurements were made using a hand-held Helley-Smith sampler at five sites during a moderate runoff event in 1992. The limitations of the Helley-Smith sampler in cobble bed channels are recognized and have been described here and elsewhere; however, the need for sampler portability between sites and ease of use during wading took precedence over the need for capturing the occasional cobble transported. The original intent was to compare transport rates between constrained/unconstrained sites in diverted/free-flowing segments. However, as no flow was diverted during peak runoff, no difference in transport rates were detected between diverted and free-flowing sites. Still, as 1992 was a relatively low flow year, peak flow and, hence, transport rates, were actually representative of the diverted period, while discharge and transport at the free-flowing sites were probably low. As a result, records from all five sites could be used to characterize transport under reduced or moderate flows.

Transport rates between constrained and unconstrained sites were quite similar, though slightly larger samples were collected at one of the constrained sites. However, differences in the timing of transport were evident, with the earliest movement occurring on the rising limb of the hydrograph at unconstrained sites and on the falling limb at constrained sites. Most of the material was fine to medium gravels and sands which moved at all sites under a variety of flow conditions (τ_*, between

0.02 and 0.07); Andrews and Smith (1992) describe such transport as "marginal". Coarse gravel moved infrequently, occurring primarily at site 3, the most unconstrained site with, presumably, the most mobile surface. As several samples from site 3 constrained coarse particles which approached the median bed particle size, it is suggested that the bed was "partially" mobile even under reduced flows (Wilcox and McArdell, 1993). No cobbles were trapped at any of the sites, indicting the larger particles remained immobile; the stability of these particles was confirmed in the painted rock study. In summary, it appears that, under reduced or moderate flows, cobbles remain immobile, gravels are partially mobile, and sands and fine gravels are in motion, passing over a stable bed.

Comparisons with theoretical transport equations (e.g. Parker and others, 1982) are in progress. Predicted transport rates should be quite low as many of the (theoretical) conditions required for mobilization were not met under 1992 flows. For example, data used by Parker and others (1982) in developing the bedload transport relations were initially screened to ensure that the bed surface was in motion. 5% of the bedload sample was to consist of particles close to the median bed particle size and 35% of the sample was to be greater than 2 mm. Only one sample from this study comes close to meeting that criterim, indicating that conditions necessary for entraining the majority of bedload were not met.

Changes in channel morphology were, for the most part, subtle and difficult to separate from any occurring naturally in the catchments examine here. The inability to identify reduced channel capacity downstream of flow diversions was probably due, in part, to the methods used as mountain streams do not follow typical hydraulic geometry relationships. While channel dimensions can be adequately predicted given the discharge (Andrews, 1984), there is considerable variance due to influences of local controls and the relative stability of subalpine channels, especially in the steepest systems. Channel capacity measured in diverted channels fell within the range of variance, indicating no significant differences. Without detailed documentation of channel dimensions prior to diversion, such as survey data or suitable photographs, our ability to document subtle changes is sharply curtailed using only theoretical or empirical methods. Additionally, the decadal time frame used here may not be appropriate as centuries may pass before significant reductions in the flow conduit are realized.

A more detailed study of channel morphology at the channel unit scale for St. Louis Creek was able to tease out some of these subtle effects. The primary change was a loss of channel surface area at unconstrained sites. This is due to (1) infrequent inundation of channel bars, (2) vegetation colonization of stable channel surfaces, and (3) the development of a low, vegetated surface beneath a formerly active cutbank. These changes translate into a 35 to 50% difference in between the cutbank and active channel widths at some pools, riffles, and rapids. Partial transport of the more mobile bed fractions is one process by which the channel adjusts it's morphology to reduced flows. In unconstrained sites, the transport effort is concentrated in the central portion of the channel, which remains active, while the lateral portions are no longer reworked. No partial transport of coarse material or change in morphology was detected at constrained sites. This is probably due to the relative infrequency with which the coarse bed is entrained and the absence of exposed lateral surfaces colonized vegetation.

Physical changes in the channel structure, such as loss of pool and riffle area, is but one way in which diversion can effect aquatic biota. While periodic sustained transport events are important for maintaining an adequate flow conduit and retaining channel structure, maintaining a critical low flow is equally important for many ecological processes. Analysis of the gage records shows a substantial depletion of the summer flows in many years which may have a detrimental impact on several aquatic species. Brook trout and cutthroat trout require adequate depth, cover, and temperatures, especially during summer months as seasonal runoff begins to wane. Diverting flows during this critical period may result in absence of cover and increased temperatures as flow is concentrated in the middle of the channel away from the banks and shade. Loss of suitable depth may occur as discharge is reduced. For other species, maintaining a constant flow level is critical. For example, macroinvertebrate emergence during waning flows may be interrupted by rapid changes in discharge at unexpected times from flow uptake and releases. The potential for change in structure and function of the aquatic ecosystem in diverted systems is, therefore, only partially dependant on the physical structure of the channel.

Additional work

The results presented here are from the first year of a continuing study on flow dynamics, sediment transport, and the effects of diversion on channel morphology and aquatic and riparian habitat at the Fraser Experimental Forest. Similar studies of bedload movement on the main stem of St. Louis Creek were conducted during peak runoff in 1993 and are planned for 1994. Bedload and velocity samples were also collected on several gaged tributaries to provide insight into sediment routing through the St. Louis catchment. In addition, a study of the diversion impacts on the growth rate of riparian vegetation, conducted by Drs. Wayne Sheppard and R.A. Schmidt of the Rocky Mountain Research Station, is under way. Finally, a baseline study on the affects of changes in flow regime on aquatic macroinvertebrate populations is proposed for the 1994 field season.

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