United States
Department
of Agriculture

Forest Service

**Rocky Mountain
Research Station**

Research Paper
RMRS-RP-20

February 2000

Stream Channel Responses to Streamflow Diversion on Small Streams of the Snake River Drainage, Idaho

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Abstract

Bohn, Carolyn C.; King, John G. 2000. **Stream channel responses to streamflow diversion on small streams of the Snake River drainage, Idaho**. Res. Pap. RMRS-RP-20. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 19 p.

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Keywords: diversions, flow indicators, Snake River basin, channel effects

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Stream Channel Responses to Streamflow Diversion on Small Streams of the Snake River Drainage, Idaho

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Introduction

Alluvial channels form and change in response to the streamflow and sediment they convey (Leopold 1994; Leopold and others 1964; Schumm 1977). Channel adjustments are usually represented by changes in measurable indices such as channel width, depth, slope, and roughness, and are believed to result from a disturbance in the balance of streamflow energy and sediment transport. It has been suggested that reducing streamflow without reducing sediment load will necessitate sediment deposition below the point of flow reduction. It is further hypothesized that vegetation can then establish on previously inundated or periodically scoured surfaces, increasing the channel bed friction, and thus facilitating sediment deposition and reducing channel size. These channel adjustments may affect the channel's ability to convey the range of flows carried by the channel before flow reductions. Since aquatic and riparian life depends on the patterns of sediment accumulation, channel geometry, and flow regimes, the biotic component of the stream system may also be impacted by altered flow levels. Downstream responses to large impoundments range from reduced channel capacity and sedimentation to channel degradation (Collier and others 1996; Gregory and Park 1974; Petts 1984; Petts and Greenwood 1985; Williams and Wolman 1984). The consequences of small, low-head seasonal water diversions remain poorly understood.

Objectives

The objectives of this study were to determine if changes in flow conveyance, substrate sediment size distribution, or streamside vegetation density occur from small, low-head water withdrawal from forest streams in the Snake River drainage. Previous studies of small diversions in Wyoming and Colorado (Chavez 1996; Ryan 1997; Wesche 1991) found some changes in channel dimensions when as much as 40 to 50 percent of flow was diverted over long periods. Most of the streams examined in this study have a small portion of the annual hydrograph diverted all or part of the year, usually with minimal instream structures and little or no impoundment. This is in contrast to dams and large diversions that alter peak flows significantly. Because channel width and depth may vary naturally within small distances, flow conveyance was selected as a parameter for this study; flow conveyance is independent of natural variation in channel dimensions.

Literature Review

Recent controversies over instream flows have resulted in a few studies of water diversions on low-order streams. In 1988 and 1989, the USDA Forest Service studied stream channels above and below water diversions on 20 streams in Colorado (Chavez 1996). Physical characteristics such as pebble size, bankfull area, width and depth, streamflows, and channel gradients were measured above and below the diversions. Between 72 percent and 91 percent of the streams showed decreases in all parameters below the diversions, supporting the theory of channel changes in response to water diversion.

Ryan (1997) investigated several subalpine channels with diversions in the Colorado Rocky Mountains. Approximately 40 to 60 percent of the annual water yield had been diverted from these streams for a number of decades, although high flows of a 5 to 50 year return frequency may have been allowed to pass. Ryan examined a number of channel attributes of diverted and undiverted stream reaches without detecting consistent changes. At the subreach channel-unit scale, she was able to detect either the formation of a low surface or a line of vegetation, coincident with the new 1.5 year flow level within the former cutbanks of diverted streams. To Ryan, this implied a loss of "functioning width" where former channel bottoms were no longer inundated regularly. These changes were limited to wider, unconstrained, pool-riffle channels with gravel bars. Narrow, steep step-pool channels were not measurably affected.

A study of channel geometry in Wyoming indicated that depth, area, and conveyance capacity were reduced below water diversions in channels with gradients less than 1.5 percent (Wesche 1991). Channel width and mean depth decreased on these channels, which reduced conveyance capacity from an average of 270 c.f.s. to an average of 123 c.f.s. Approximately 46 percent of the flow had been diverted for an average of 66 years from at least six of the 20 low-gradient channels studied. The age of the diversion was not a significant factor, perhaps because all but one diversion were over 50 years old. Channel geometry and bed composition of the seven streams with gradients greater than 1.5 percent did not differ significantly above and below the diversions after more than 35 years of an estimated average flow reduction of 70 percent.

Some fluvial geomorphologists hypothesize that reducing streamflow without reducing sediment load will induce channel changes through sediment deposition below the point of flow reduction. This hypothesis derives from Wolman and Miller's work (1960) linking flood frequency and sediment transport rate. They proposed using the product of the frequency of flow events and the sediment transport rate as a measurement of the amount of geomorphic work performed by events of different frequencies and magnitudes. Their analysis of selected rivers showed that most of the long-term sediment loads were carried by moderate, but relatively frequent, events. These moderate events occur about every 1 to 2 years, and often approximate the bankfull stage. Larger, more powerful events move sediment at a higher rate, but occur less frequently. Over time, the sum of the sediment moved by the moderate flows outweighed the amount moved by larger events, and thus is thought to play a more significant role in shaping the channel. Wolman and Miller (1960) referred to these moderate flows as "effective" discharges. The concept of effective discharge has become a fundamental model of geomorphic work.

The frequency of effective discharge was corroborated by Andrews (1980), who compared the effective discharge to the bankfull discharge (the discharge that filled the channel to the level of the floodplain) at 15 gaging stations in the Yampa River basin in Colorado and Wyoming. The recurrence intervals of the effective discharges were between 1.18 and 3.26 years, and nearly equaled the bankfull discharges at all gaging stations. Andrews and Nankervis (1995) also found agreement between the field-determined bankfull discharge and the computed effective discharge for 17 alluvial gravel-bed streams throughout the Rocky Mountain region. Eighty percent of the long term mean bedload was transported by discharges ranging between 0.8 and 1.6 times the bankfull discharges. By measuring bedload over a 6 year period, Carling (1988) also found that the "dominant discharge," or "that discharge which transports most bed sediment in a stream that is close to steady-state conditions," was close to bankfull discharge. Overbank flows were important in initiating channel change. Carling emphasized that his findings did not apply to "streams that are unable to adjust their form freely or are out of equilibrium." Most recently, Whiting and others (1997) confirmed that the effective discharge for headwater streams in central and northern Idaho averages about 80 percent of bankfull discharge and has a recurrence interval of 1.5 years. Flows lower than 80 percent of bankfull accounted for very little of the sediment movement on these Idaho streams. The modest magnitude of the effective discharge suggests that even small diversions could reduce streamflow sufficiently to alter channel form.

Sediment may also be shunted out of the stream by some diversion structures. Johnson and Smith (1979) estimated that 15 irrigation ditches in a small irrigated valley in southwestern Idaho diverted as much as 560 t (metric ton) of suspended sediment from the main streams each year—about 17 percent of the total sediment load of the monitored streams.

The connection between streamflow and streamside vegetation communities along low-order streams has also raised questions about the effects of diverting streamflow. Harris and others (1987) reported increased shrub cover and decreased vegetated channel width along some diverted streams in the Sierra Nevada, CA. Such vegetation encroachment could increase channel roughness, inducing sedimentation. While the direct effect of roughness due to vegetation on flow velocity is poorly understood, there is evidence of sedimentation due to in-channel vegetation.

King (1961) reported aggradation accompanied by pioneering vegetation within a Wyoming channel. The stream reach he studied was below the confluence of an ephemeral stream that had been dammed. He suggested that reduced inflow from the tributary caused sedimentation that was followed by vegetation pioneering on the deposition, and that the vegetation then induced further sedimentation. Flume experiments simulating herbaceous vegetation in a low-gradient stream support entrapment of fine sediment (median grain size 0.09 mm) by some vegetation (Abt and others 1994; Clary and others 1996). They found that, for their test conditions, vegetation significantly increased sediment deposition and retained 30 to 70 percent of deposited sediment during flushing flows. The length of the vegetated strip and the height of the vegetation were important variables.

Masterman and Thorne (1992) developed a theoretical procedure to predict the effect of bank vegetation on channel capacity. In their analysis, flexible, 0.8 m high plants reduced channel discharge capacity more than 5 percent in channels with width-depth ratios less than 9. Channels with width-depth ratios less than 16 may also be significantly affected.

Not all research supports the encroachment of vegetation into channels carrying reduced streamflows. Stromberg and Patten (1990) reported a strong positive relationship between tree growth and streamflow volume (or stream stage) for riparian species in the eastern Sierra Nevada, CA. In Wesche's 1991 study of small, low-gradient streams in Wyoming, about half of the 20 streams examined showed no change in the canopy, shrub, or grass densities below the diversions. Of the streams that appeared to respond vegetatively to reduced flows, approximately equal numbers showed increases and decreases in the canopy and shrub densities. The density of grass decreased at six streams, but increased at only two streams. Plant density decreased most often in low-gradient channels where the vegetated area increased due to encroachment. The effects of water diversion on the width of the riparian corridor were modeled on small streams in the arid eastern Sierra of California (Taylor 1982). Water diversion in this study apparently created drought stress; diverting 25 percent of the flow significantly decreased the extent of riparian vegetation. For diversions greater than 25 percent of the flow, the loss of vegetation was related to the amount of water diverted. Although the composition of the vegetation communities were not measured or modeled, Taylor suggested that because streams with larger flow rates support more complex vegetation communities, streams experiencing reduced flows would lose vegetative complexity.

Plant water stress in response to water diversion was also studied by Smith and others (1991) at two sites in the eastern Sierra Nevada. Water stress indicators were measured in a high runoff year and a low runoff year. About 9 to 33 percent of the streamflow was diverted at one site, and 70 to 98 percent was diverted at a second site. Their data suggested that soil water at sites with high diversion rates was not sufficient to meet peak evaporative needs late in summer.

Leighton and Risser (1989) developed a vegetation model that indicated little physiological plant stress occurred until a significant reduction in streamflow was achieved. Young plants were the most vulnerable. Isotope analysis of tree xylem water suggested a shift in water source from soil water in May, to surface water in July, to ground water in September.

Perhaps the literature addressing riparian plant responses to reduced streamflow is best summarized by Harris and others (1987), whose report on plant communities along diverted streams stated that "…riparian communities in the Sierra Nevada respond in an individualistic manner to hydroelectric diversions. This could be true in other mountainous regions of the western USA as well."

Site Selection and Sampling Design

The diversion sites selected for this study are on low-order forest streams on public land in the Snake River drainage (fig. 1). Most are located throughout southern and central Idaho, but four are in eastern Oregon and one is in western Wyoming. A list of potential study sites was initially developed by asking Forest Service and Bureau of Land Management hydrologists for locations of diversions on public land with flows low enough to wade in summer, channels undisturbed by channelization, riprap, or severe grazing, and without flow regulation by upstream reservoirs or major diversions. We eliminated candidates with clearly different stream types above and below the point of diversions to accomodate paired studies (above

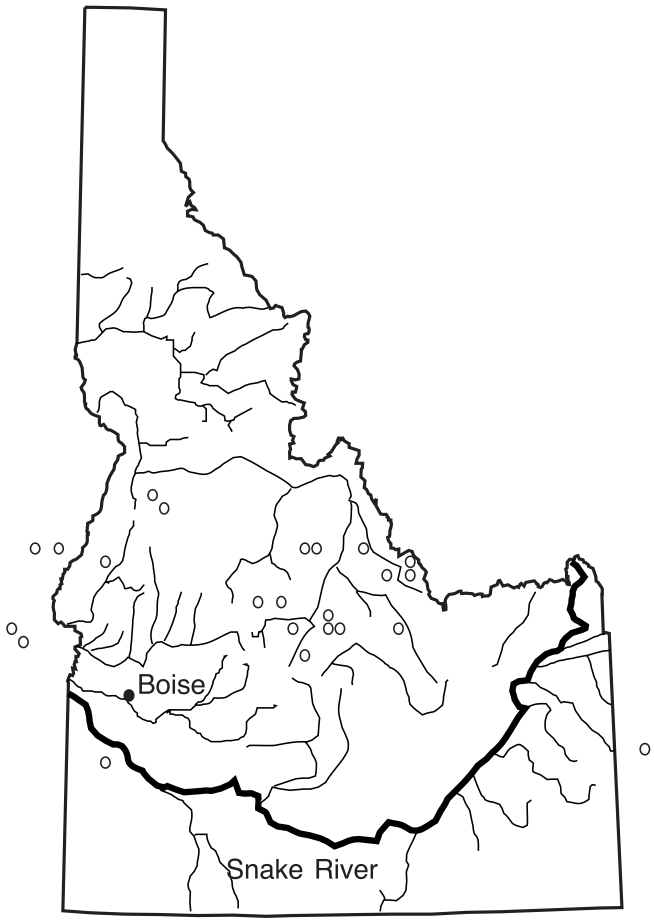

Figure 1—Location of diversion study sites.

versus below). Because diversions are often located at a break in stream gradient, this was a difficult criterion to satisfy, but variablity between pairs was minimal (table 1). Other candidate diversions were added from lists of water rights and by chance discovery. Each candidate was evaluated by field inspection, resulting in the selection of 21 sites on low-order, snowmelt-driven forest streams, with gradients ranging between 0.3 percent and 10.7 percent, and bankfull flows ranging between about 2 c.f.s. and 101 c.f.s. (table 1). Seventeen sites were initially sampled in 1993; an additional four sites were located and sampled in 1994.

Most diversions were low structures of wood, concrete, or rock and tarps (fig. 2). Some had headgates and others appeared to be reconstructed each spring. Rarely, small earthen dams that captured essentially all flow were found. Hydrologic records were not available for any of the study sites, but observations, brief conversations with a few irrigators, and some measurements in spring 1995 suggest a wide variation in amount and period of diversion. Although the water rights associated with many of the diversions were located, the histories of actual use could not be determined. A few of the water rights dated back as far as 1876 or as recent as the 1960's and 1970's, but most originated between 1900 and 1935. The exact site of the older diversions may have changed, and some use may have been discontinuous, depending on cultural and climatic conditions. Most structures appeared to pass spring snowmelt flows of bankfull and higher, and probably diverted only a portion of summer flows. Some appeared to divert flow throughout the year.

Each stream site was divided at the diversion into above "A" and below "B" stream reaches (fig. 3). This type of reach pairing was chosen because local variations could distort comparisons between groups of diverted streams and groups of free-flowing streams. In addition, a third stream reach, designated "C," was established upstream of "A" at seven sites to determine the relevance of spatial variability of the stream characteristics. All "C" data were collected in 1994, while the "A" and "B" data from the same sites were gathered in 1993. Thus, some comparisions between "A" and "C" may be confounded by spring flows of differing magnitude. Within each reach, data were collected along cross-stream transects with end points staked well above the bank of the active channel, and usually at some topographical break. The transects were spaced two stream widths apart, beginning as close to the diversion as possible while still avoiding diversion influences such as ponding above or scour holes below. Most reaches had five transects; sites surveyed in 1994 had three transects, and occasionally, a 1993 site changed stream type before five transects spaced properly were staked, and so fewer transects were surveyed. Data were gathered on channel geometry and bed-surface particle-size distribution at all the transects. Flow discharge at time of survey (low flow), channel gradient, and vegetation density and stem size data were collected from the first and last transects of each reach.

In addition to the extensive sampling in the summers of 1993 and 1994, flow and sediment discharge were sampled at accessible sites during the 1995 spring runoff. Discharge, gradient, bedload, and suspended sediment samples were collected from 10 sites during spring 1995, and pebble counts were made in the summer after the flow had receded.

Methods

Flow Conveyance

Many diversion structures are placed in locations associated with change in the channel, such as a change in the slope or a change from confining valley walls to a broader valley floor. Although sites for this study were selected to minimize the effects of placing

Table 1—Study site characteristics.

Site name	Slope at frequent flow elevation			Width at frequent flow elevation			Estimated discharge frequent flow			Estimated discharge edge of vegetation			D_{50} of B axis			Diverted spring 1995[a]
	Above A	Below B	Above C	Above A	Below B	Above C	Above A	Below B	Above C	Above A	Below B	Above C	Above A	Below B	Above C	
	percent			*m*			*c.f.s.*			*c.f.s.*			*mm*			*percent*
Pole	0.3	0.6	0.4	5.05	4.93	4.15	64	30	76	42.87	20.89	39.69	16-32	16-32	16-32	2
Boone	0.3	0.7		6.22	7.80		74	75		118.3	113.7		16-32	32-64		
Valley	0.6	1.2	0.9	6.74	5.47	8.79	48	36	79	33.64	50.63	104.5	32-64	64-128	32-64	14
North Fork Burnt	1	0.4	1	13.93	15.47	16.38	56	11	132	75.51	17.68	14.18	64-128	64-128	64-128	
Knapp	1.2	0.6	0.2	6.19	6.84	6.91	55	49	65	32.78	26.11	35.12	32-64	64-128	32-64	1
Upper Champion	1.3	1		4.74	4.92		18	26		4.68	13.84		22	25	10	
McDevitt	1.6	1.5	6.5	2.83	2.14	2.59	10	3	18	22.09	3.03	10.54	16-32	8-16	16-32	
Hawley	1.7	1.6	4.3	5.04	2.92	5.15	28	1	37	19.74	1.43	26.93	32-64	<0.062	16-32	100
Boulder	1.7	2.4		6.24	8.59		57	32		62.84	39.88		128-256	32-64		
Alturas	1.7	1.1		17.74	13.59		101	89		127.8	93.81		128-256	64-128		
Upper Hawley	1.8	2.8		5.34	4.33		60	30		66.65	9.28		51.5	40		6
Lower Champion	2.3	2.63		3.24	3.50		21	21		9.2	9.95		25	34		9
West Fork Burnt	2.5	3.4	2.6	4.87	3.03	5.00	10	3	34	6.13	2.89	3	32-64	32-64	32-64	
July	3	3.1		6.54	5.67		34	34		12.63	18.35		128-256	128-256		26
Silver	3.1	2.1		1.29	1.42		5	6		4.1	6.03		8-16	2-8		
Morgan	3.5	1.7		2.84	3.76		15	9		19.74	15.39		8-16	16-32		0
Cottle	3.7	3		1.83	2.19		2	2		0.54	1.99		62.5	9		
Cottonwood	7.3	8.1		6.31	4.62		36	34		101.4	67.86		128-256	256-512		
Van Horn	10.5	9		3.02	3.50		17	10		26.5	21.23		32-64	32-64		7
Eagle	10.6	6.6		7.04	6.32		72	56		174.9	176.1		128-256	128-256		
Ethel	10.7	8.2		13.00	12.00		3	3		2.74	2.93		32-64	.062-2		

2a. Pole Creek—The canal, with a headgate, is on the right.

2b. July Creek—The canal is on the right, blocked with a tarp and wood.

2c. Hawley Creek—Willows are growing on the earthen dam that fully diverts the creek into a canal.

2d. West Fork Burnt River—A low structure across the stream channel diverts water at low flow into the canal to the right.

2e. Knapp Creek—A wooden structure, with a headgate, blocks the entrance to the canal.

2f. Cottonwood Creek—Rocks and sandbags across the channel divert water into the canal at low flows.

Figure 2—Examples of diversion structures.

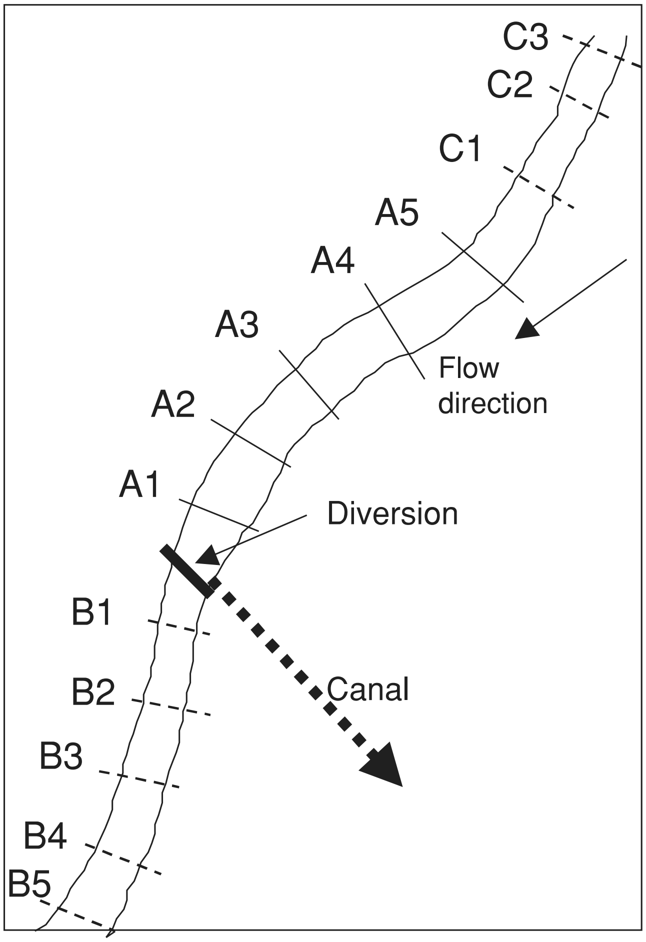

Figure 3—Sampling design.

diversions at breaks in channel gradient or type, channel characteristics such as width and depth may not always be directly comparable above and below the point of diversion. The conveyance capacity of stream channels should remain constant over short distances because the volume of water that must be conveyed remains relatively constant. Because a change in conveyance capacity is a good indication of channel changes, conveyance capacity was selected as the main test criterion. If the flow is reduced and sediment is deposited, channel response should be detectable by comparing the conveyance capacity in the undisturbed channel above the point of diversion to the conveyance capacity below the diversion.

Channel gradients were determined from the thalweg distance between the first and last transects of each sample area. Elevation changes were measured with a surveyor's level and rod at the elevation of a feature approximating bankfull. (The feature used was called "frequent flow" and will be defined later in this section.)

Streamflow and channel geometry were measured at 21 sites in the summer of 1993 or 1994. There is not a standard method for estimating the discharge of mountain streams. Hydrologists differ on how to estimate velocity because the energy dispersed by friction and turbulent flow over rocks and bedforms is difficult to estimate. Williams (1978) evaluated several methods of estimating bankfull discharge at ungaged sites, and concluded that the best estimates were from his empirical formula ($Q_b = 4.0A_b^{1.21}S^{0.28}$), which uses slope, channel cross-sectional area, and coefficients derived from regression of 233 bankfull discharges. Jarrett (1984, 1990) developed a similar equation, estimating discharge from area, hydraulic radius, and slope, but using different coefficients that were empirically derived specifically from small mountain streams. Jarrett's equation ($Q = 3.81AR^{0.83}S^{0.12}$) was developed from streams with slopes ranging from 0.2 to 4.0 percent , and hydraulic radii ranging from 0.15 to 2.1 m. It assumes no backwater and relatively low suspended sediment levels. Jarrett's equation was used to estimate streamflow in this study because the necessary assumptions were met well, and estimates were reasonable. The assumptions for Jarrett's equation were violated only by slopes on two of the study streams that exceeded 4.0 percent (table 1), and hydraulic radii less than 0.15 for five study streams at "frequent flow" stage.

The appropriateness of Jarrett's equation for the streams in this study was verified by testing estimates made with the equation against instantaneous spring runoff flow measurements at 10 of the 21 sites in 1995. Although some estimates varied substantially from measured flows, most estimates were within the expected range of error, based on variances in Jarrett's data set (fig. 4). The equation performed best with high flows, although it tended to underpredict the high flows. Only data collected above diversions were used to test the performance of the equation.

Two channel features were used to define the stage elevations for calculating conveyance estimates, "frequent flow," and the edge of vegetation. "Frequent flow" is a term used in this study to refer to a frequently occurring flow, which probably coincided with the bankfull stage at most locations. The frequent-flow elevation was identified by a series of indicators on the banks such as change in vegetation, bank topography, or bank sediment sizes. These indicators are sometimes used to identify bankfull (Harrelson and others 1994); however, the definition of bankfull may vary depending on the application. The frequent-flow elevation is usually approximately the same elevation as the tops of local channel bars.

The other channel feature used as a stage elevation for discharge estimates was the edge of vegetation.

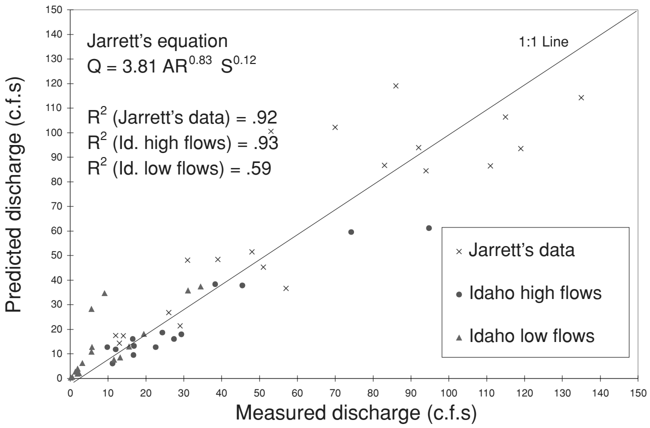

Figure 4—Fit of predicted flow using Jarrett's equation.

The average flow within the edges of vegetation was used because of the interest in reduced conveyance capacity due to vegetative encroachment. The flow discharges at the elevation of frequent flow and the edge of vegetation on both the right and the left banks were calculated using Jarrett's (1984, 1990) equation and averaged for the transects above each diversion, and then for the transects below. The edge of vegetation was defined as the edge of rooted vegetation, including grasses.

Discharge estimates at each stream were pooled into group "A" for above the diversions and group "B" for below the diversions, and then tested for normal distribution. Because normality for both the frequent flow groups and the edge-of-vegetation groups was rejected, differences between "A" and "B" were tested with the Wilcoxon signed-rank test. An analysis of spatial variability in flow discharge was also conducted using the seven "A" and "C" pairs. Although the "A" and "C" pairs were normally distributed, they were tested by Wilcoxon signed-rank tests for uniformity. Data for the "A" transects for all members of this subset were recorded in 1993, while all "C" measurements were recorded in 1994.

Substrate

Changes in particle-size distribution of the channel bed may indicate deposition due to reduced streamflows. Deposition can eventually alter the channel geometry and the channel capacity for conveying flows. The pebble-count technique (Kondolf 1997; Wolman 1954) is an accepted method of characterizing the particle-size distribution of a bed surface. It uses an impartial collection of at least 100 samples gathered along a grid or transect to represent the population of pebbles. Care must be taken, however, to not bias the sample against particles less than 15 mm (Fripp and Diplas 1993). The pebble count method can also be subject to variation due to different operators (Wohl and others 1996).

Particle-size distribution data were gathered by the Wolman (1954) pebble-count method along established cross-section transects. Sampling began at the frequent-flow elevation on one bank and ended at frequent flow on the other bank. Pebble samples were equally spaced along the transect and selected with a pointer as the sampler looked away. The B-axis (the intermediate size axis) and the vertical height of the pebble above the bed surface (z) of approximately 20 evenly spaced pebbles were measured at each transect in 1993 or 1994. B-axis lengths were recorded in size classes in 1994, and in millimeters in 1995 (see table 2 for list of size classes used). Vertical heights were recorded in millimeters. Data within each reach ("A," "B," and "C") were pooled for a total of at least 100 point samples representing bed surface sediments in each area. Wilcoxon signed-rank tests and Chi-square tests were used to determine differences in particle-size distributions of the B-axis measurements above and below diversions. The D_{50} and D_{84} of the samples were determined and tested. D_{50} is the particle diameter size that is equal to or greater than 50 percent of the particle diameters. D_{84} is equal to or greater than 84 percent of the particles sampled. Both D_{50} and D_{84} are often used to represent particle-size distributions for comparisons of reaches or over time. Channel-bed roughness (Bathurst 1985; Ugarte and Madrid 1994; Wiberg and Smith 1991), represented by the ratio of the vertical pebble height to hydraulic radius (z:R), was also tested for significant differences between "A" and "B," using Wilcoxon signed-rank tests.

Vegetation

Vegetation analyses focused on the location, density, and diameter of plant stems. These data were used to establish the edge of vegetation for flow estimates and to represent plant cover and vigor above and below diversions. Vegetation data were collected at 17 diversion sites in 1993, and at the seven "C" streams in 1994. Data were collected at low flows in a 1-foot wide band across the channel at transects 1 and 5. The bands extended from the ends of the transects, located at the top of channel banks, to the edges of vegetation at the channels. Stem counts were made in two vertical layers, 0 to 6 inches (Layer 1) and >6 to 48 inches (Layer 2) from the ground. Only woody stems were counted; no grasses or herbaceous growth were included. All stem diameters equal to or greater than 1 cm were measured and recorded, and diameters less than 1 cm were tallied. Dead logs and branches were counted, but if they were greater than 1 cm in diameter, they were excluded from the analysis.

Table 2—Pebble-count size classes.

Size classes	For sites:	Size classes	For sites:
mm		*mm*	
<0.062	Eagle	<0.062	Pole
.062-<2	Ethel	.062-<2	Boone
2-<8	Silver	2-<8	Valley
8-<16	Cottonwood	8-<16	North Fork Burnt
16-<64	Boulder	16-<32	Knapp
64-<256		32-<64	Upper Champion
256-<512		64-<128	McDevitt
512-<4096		128-<256	Hawley
		256-<512	Upper Hawley
		512-<4096	Lower Champion
			West Fork Burnt
			July
			Morgan
			Cottle
			Van Horn
			Alturas

The data were analyzed using Wilcoxon signed-rank tests of "A" against "B." Stem density and average stem diameters above and below the diversions were stratified by layers and stem sizes (<1 cm and = >1 cm) for the analysis.

Sediment Transport

Ten streams were revisited in the spring and fall of 1995. Bedload and suspended sediment samples were gathered at high flows above and below these diversions on at least 1 and up to 4 days in the spring, and Wolman pebble counts were made during lower flows in the fall. Both sediment samples were collected along the same transects at equally spaced verticals, with equal sampling time (bedload) or transit rate (suspended sediment) at each sample vertical (Edwards and Glysson 1988). Suspended sediment samples were collected with a DH-48 sampler and then filtered, dried, and weighed. Bedload was sampled with a 3 inch Helley-Smith bedload sampler using 0.25 mm mesh sampling bags. Each transect was traversed twice for bedload, and the samples from each vertical were composited but the transects were not. The samples were oven-dried, and sieved through sieve sizes 0.063, 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, and 64 mm. Each size fraction was weighed to calculate percent of total sample, and the results of each size fraction from the two traverses were averaged. Particle diameters less than 0.25 mm were not included in the analysis because they were smaller than the mesh size of the sample bag. The percent fines (0.25 to 0.5 mm) were calculated for all samples; rate of bedload transport (g per min) for the full stream width was calculated from the samples that had accompanying stream-width data. For uniformity, Wilcoxon signed-rank tests were used to compare sediment loads above and below all diversion sites for both normally distributed data and where normal distribution of the data was rejected.

Results

Flow Conveyance

Figure 5 shows the estimated conveyances at frequent-flow level, plotting flows above and below each diversion against each other. The plot indicates that conveyances above diversions are generally larger

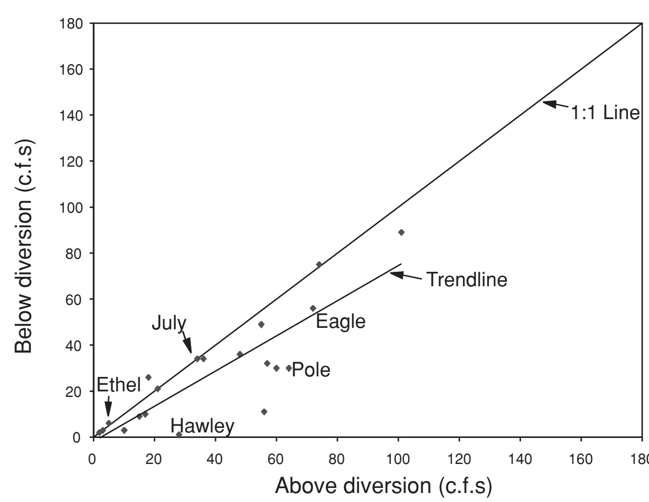

Figure 5—Frequent flow discharge, above versus below diversions.

than their paired reaches below. The two-tail Wilcoxon signed-rank test of "A" and "B" pairs was significant (table 3). The paired T-test of the seven "C" sites paired with the appropriate "A" data was also significant at p = 0.0180 (table 3), which suggests natural spatial variation independent of the diversion. Further examination of the data revealed that flow below was about 7 c.f.s. less than above the diversions, while flows in "C" reaches averaged 24 c.f.s. more than in the "A" reaches. Most likely, this huge disparity between "C" and "A" reaches is due to temporal or observer differences rather than spatial differences because these reaches were surveyed in different years and by different crews. This underscores the difficulty in uniformly identifiying the frequent-flow indicators, particularly following spring runoffs of differing magnitudes. Identifying frequent-flow indicators may be more subjective than is acceptable for research purposes.

The second method for estimating channel conveyance, surveying the elevations of the edge of vegetation, is less subjective than identifying frequent-flow indicators. Figure 6 provides a comparison of edge-of-vegetation conveyance above and below diversions. The plot of these data suggests that flow above diversions is greater than below, and that the disparity tends to increase with the size of the discharge above. The Wilcoxon signed-rank test of edge-of-vegetation data from all 21 paired reaches was significant at p = 0.0106. "A" and "C" data showed no significant difference (P = 0.7353), despite being measured in different years and by different crews (table 3). The mean difference in flow conveyance between reaches "A" and "B" was about 15 c.f.s.; the difference between "A" and "C" reaches was 0.2 c.f.s. The means displayed in table 3 suggest an overall reduction in conveyance below diversions of about 30 percent by edge of vegetation estimates, and about 19 percent by frequent-flow estimates. No relationship between channel slope above diversions and the percent change in estimated edge of vegetation flows was detected in these data (fig. 7).

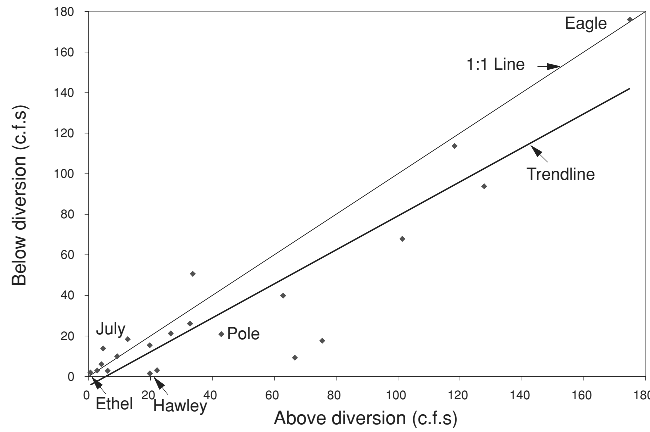

Figure 6—Edge of vegetation discharge, above versus below diversions.

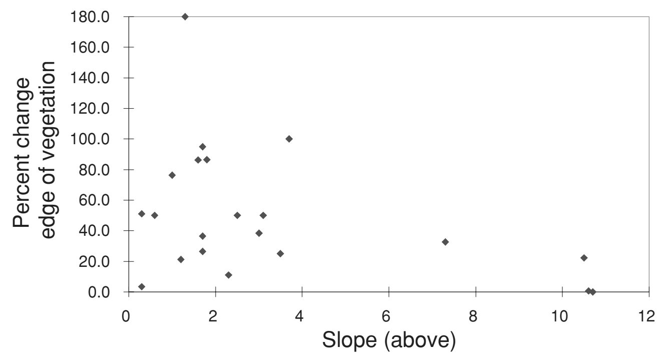

Figure 7—Slope versus percent change in edge-of-vegetation discharge diversions.

Substrate

Changes in pebble-count particle-size distributions were first tested by Wilcoxon signed-rank test on the percent of pebbles 0 to 2 mm, and 0 to 8 mm. The finer fraction was thought to be the most likely size range to respond to flow reductions because it was the most

Table 3—Tests of flow discharge.

Test	Variables	n	Means (standard error)	p value
Frequent flow	Above, below	21	42.0(6.6), 34.2(8.4)	0.0113[a]
	Above, C	7	38.7(8.5), 63.0(14.4)	.0180[a]
Edge-of-vegetation	Above, below	21	51.6(11.0), 36.2(9.7)	.0106[a]
flow	Above, C	7	33.3(8.3), 33.5(12.8)	.7353

[a]Significantly different at 95 percent level.

abundant size by weight in the sediment transport samples. Although the average percent of the fine fraction was somewhat larger below the diversions, the tests were not significant in any of the test years (table 4). Tests of D_{50} and of D_{84} also failed to distinguish any significant differences between reaches above and below the diversions (table 4). Nonetheless, large differences in the percent of fine material were found between "A" and "B" at some of the individual sites (fig. 8, 9), so the "A" and "B" pairs at each individual diversion were examined by Chi-square tests for sizes less than 8 mm and less than 32 mm (table 5). Ten of the 21 streams had significantly different ($p = 0.1$) percentages of particles 0 to 8 mm above and below the diversions. Thirteen of the 21 sites showed significant differences between "A" and "B" for particles 0 to 32 mm. Of the 7 "C" sites, none differed significantly from its "A" reach in the 0 to 8 mm group, and only 2 differed significantly in the 0 to 32 mm group (table 5). Some of these streams, however, had significantly finer material above the diversion; others were finer below (fig. 10).

A series of Wilcoxon signed-rank tests were used to search for changes in channel-bed roughness. The D_{50} and D_{84} of the vertical axes (z) from the 1993 to 1994 pebble counts were used with the estimated hydraulic radius (R) or frequent flow in a ratio z:R. The D_{50} and D_{84} measures of the vertical axes from 1995 pebble counts were also used in a ratio with the R of the measured spring flows. The data were stratified by the slope of the "A" reach, so that slopes of 0 to 4 percent were in one group and slopes greater that 4 percent were in another group. Although the 4 percent breakoff was somewhat arbitrary, it was chosen because it begins a gap in the data between the steep streams (greater than 7 percent) and the rest of the streams. No significant differences between "A" and "B," and "A" and "C" were detected at the 0.05 level (table 6).

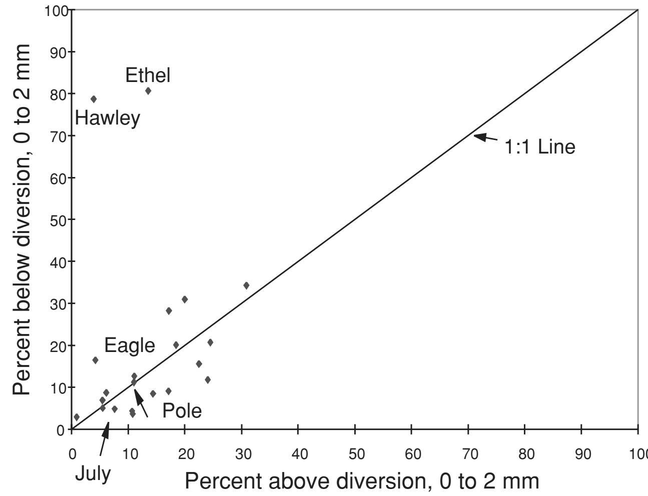

Figure 8—Percent of pebbles 0 to 2 mm, above versus below diversions.

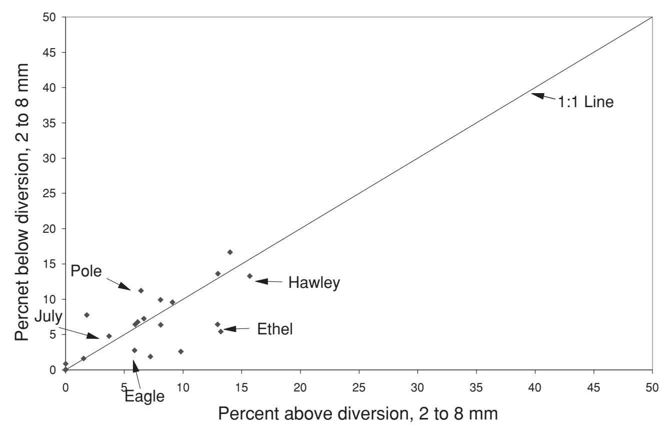

Figure 9—Percent of pebbles 2 to 8 mm, above versus below diversions.

Table 4—Tests of pebble-count results.

Test	Variables	Year	n	Means (standard error)	p value
D_{50}	Above, below	1993-1994	21	71.3(13.4), 70.4(19.3)	0.7113
	Above, below	1995	10	44.1(9.4), 44.4(8.5)	.8785
D_{84}	Above, below	1993-1994	21	33.7(9.6), 41.2(13.2)	.7815
	Above, below	1995	10	105(18.4), 114.4(21.8)	.9593
percent				- - - - *percent* - - - -	
<2 mm	Above, below	1993-1994	21	13.3(1.8), 19.8(4.8)	.6639
	Above, C	1993-1994	7	10.4(2.6), 13.5(2.2)	.1763
	Above, below	1995	10	8.1(1.4), 9.9(2.1)	.4443
<8 mm	Above, below	1993-1994	21	20.4(2.2), 26.2(5.1)	.6143
	Above, C	1993-1994	7	20.0(3.1), 20.4(2.5)	.7353
	Above, below	1995	10	15.2(2.2), 20.1(4.8)	.375

Table 5—Chi-square probabilities of 1993-1994 pebble counts. **Bold** indicates the reach with the higher percent of fines.

Site (reach)	0-8	0-32
	- - - - - - - - *mm*	- - - - - - -
Alturas (A,**B**)	.0184[a,b]	0.2157
Boone (**A**,B)	.0029[b]	.0007[b]
Boulder (**A**,B)	.1725	.0260[b]
North Fork Burnt (A,B)	.6826	.3603
West Fork Burnt (A,B)	.5538	.3120
Lower Champion (A,**B**)	.0584[b]	.0873[b]
Upper Champion (**A**,B)	.1752	.0582[b]
Cottle (A,**B**)	.0465[b]	.0086[b]
Cottonwood (**A**,B)	.0244[b]	.0070[b]
Eagle (A,B)	.7823	.2629
Ethel (A,**B**)	.0000[b]	.0000[b]
Hawley (A,**B**)	.0000[b]	.0000[b]
Upper Hawley (A,B)	.8952	.6036
July (A,B)	.6866	.4780
Knapp (**A**,B)	.0595[b]	.0042[b]
McDevitt (A,**B**)	.0664[b]	.0088[b]
Morgan (**A**,B)	.0649	.0384[b]
Pole (**A**,B)	.3576	.0110[b]
Silver (A,B)	.3759	.1464
Valley (**A**,B)	.4881	.0986[b]
Van Horn (A,B)	.0093[b]	.1824
North Fork Burnt (A,C)	.1932	.1887
West Fork Burnt (**A**,C)	.9944	.0625[b]
Hawley (A,**C**)	.9167	.4527
Knapp (A,C)	.4213	.2031
McDevitt (**A**,C)	.2295	.0208[b]
Pole (A,C)	.2087	.4152
Valley (A,C)	.3236	.5064

[a]At least one cell had <5 observation.
[b]Significant difference between Above and Below at 0.1 level.

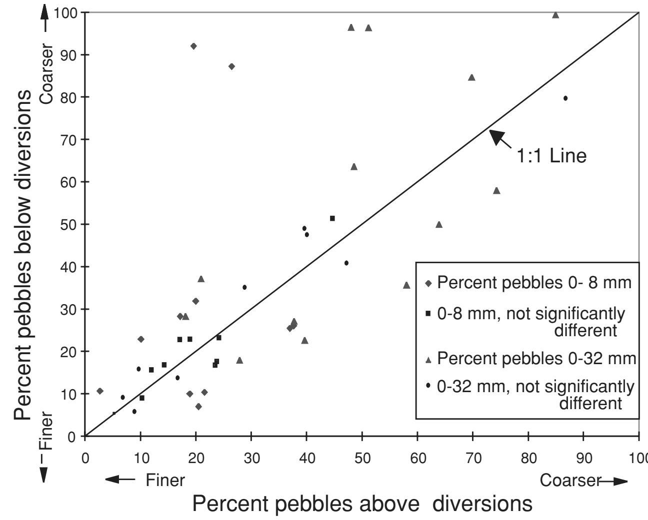

Figure 10—Chi-square analyses of pebble counts.

Sediment Transport

The Wilcoxon signed-rank tests comparing the rate of bedload transport (g per min) above and below diversions showed significantly reduced bedload transport rate below diversions (table 7). The transport rate for the finest fraction of the captured bedload (0.25 to 0.5 mm) also tested significant, although the percent by weight for the same fraction did not. When the data were stratified by whether the ditches were carrying water, the transport rate above the diversions with dry ditches was not significantly different from below, with p = 0.1282 testing all data and p = 0.1763 for the fraction 0.25 to 0.5 mm. The total bedload transport rate and the transport rate for the 0.25 to 0.5 mm fraction were significantly greater above diversions where water was being diverted into ditches (p = 0.0425 and p = 0.0630). The mean rates of transport

Table 6—Tests of roughness, pebble size: R.

Test	Variables	Year	n	Means	p value
D_{50}:R	A versus B, all data	1993-1994	21	0.1122, 0.1051	0.6389
D_{84}:R	A versus B, all data	1993-1994	21	.4250, .3584	.5202
D_{50}:R	A versus C, all data	1994	7	.0929, .0789	.0630
D_{84}:R	A versus C, all data	1994	7	.3111, .2529	.1282
D_{50}:R	A versus B, slopes 0-4 percent	1993-1994	17	.1002, .1076	.1773
D_{84}:R	A versus B, slopes 0-4 percent	1993-1994	17	.3283, .3225	.3088
D_{50}:R	A versus B, slopes >4 percent	1993-1994	4	.1635, .0944	.0679
D_{84}:R	A versus B, slopes >4 percent	1993-1994	4	.8359, .5110	.7150
D_{50}:R	A versus B, all data	1995	9	.0801, .0899	.5147
D_{84}:R	A versus B, all data	1995	9	.2347, .2776	.6784
Vertical axis D_{50}	A versus B, all data	1993-1994	21	24.19, 21.33	.3293
Vertical axis D_{84}	A versus B, all data	1993-1994	21	83.73, 70.95	.6019

Table 7—Tests of bedload transport.

Test	Variables	Year	n	Means	p value
g/min					
Rate	A versus B, all data	1995	14	497.8, 175.3	0.0085[a]
Rate	A versus B, gate open	1995	7	786.5, 219.0	.0425[a]
Rate	A versus B, gate closed	1995	7	209.2, 131.7	.1282
percent				*percent*	
Fines (0.25-0.5 mm)	A versus B, all data	1995	20	19.2, 26.8	.0897[a]
Fines (0.25-0.5 mm)	A versus B, gate open	1995	11	17.9, 27.3	.1748
Fines (0.25-0.5 mm)	A versus B, gate closed	1995	9	20.7, 26.1	.3743
mm					
Rate for 0.25-0.5	A versus B, all data	1995	14	50.0, 22.9	0.0245[a]
Rate for 0.25-0.5	A versus B, gate open	1995	7	72.6, 23.9	0.0630[a]
Rate for 0.25-0.5	A versus B, gate closed	1995	7	27.4, 21.9	0.1763

[a]Significant at 0.10 level.

above and below were relatively close when the headgates were closed and generally quite different with the headgates open, as displayed by the trend lines in figure 11. It is possible that at least some of the ditches or diversion systems may have been extracting significant portions of the bedload.

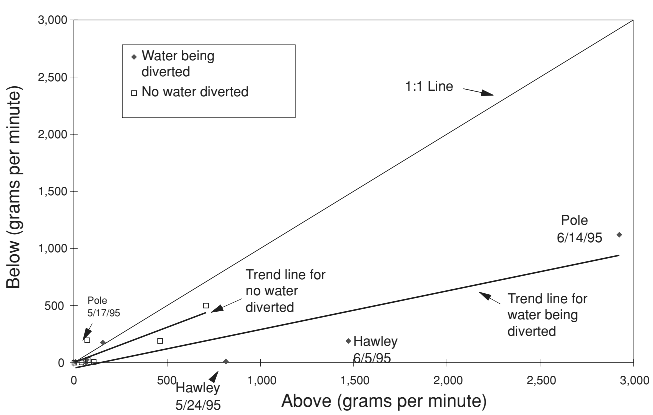

Figure 11—Bedload transport rates (average of 2 passes).

Suspended sediment concentrations were determined from the DH-48 sampler stream samples, and then converted to grams per second using accompanying flow measurements. Although large differences between the mean rates of suspended sediment discharge above and below diversions were found at diversions with open headgates, the differences were not statistically significant when tested with Wilcoxon signed-rank tests (table 8). It is an interesting observation, however, that the mean rates of suspended sediment discharge were very close when the headgates were closed, as was seen with the bedload samples.

Vegetation

Stem densities varied widely, and there was not a statistical difference between "A" and "B" data (fig. 12; table 9,10). In Layer 2 (6 to 48 inches), however, stem diameters were significantly larger above diversions than below ($p = 0.021$); diameters in this layer did not differ significantly between "A" and "C" (table 11).

Table 8—Wilcoxon signed-rank tests of suspended sediment.

Test	Variables	Year	n	Means (standard error)	p value
g/min					
Rate	A versus B, all data	1995	15	33.9 (18.2), 16.7 (5.2)	0.2524
Rate	A versus B, gate open	1995	10	42.7 (27.0), 16.2 (7.0)	.1309
Rate	A versus B, gate closed	1995	5	16.4 (8.2), 17.6 (8.2)	.6858
mg/l					
Concentration	A versus B, all data	1995	18	24.5 (6.3), 33.8 (14.5)	.7019
Concentration	A versus B, gate open	1995	11	28.3 (10.1), 38.0 (23.6)	.7646
Concentration	A versus B, gate closed	1995	7	18.5 (3.8), 27.3 (7.5)	.3980

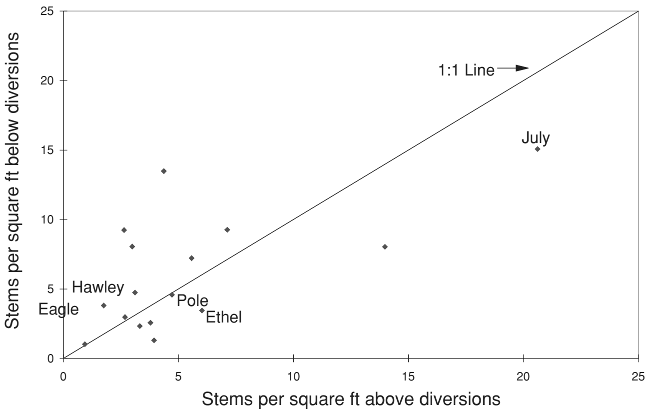

Figure 12—Average stem densities, all layers and diameter sizes.

Discussion

Flow Conveyance

The statistical tests and plots (table 3; fig. 5, 6) of flow discharges indicate reduced conveyance below diversions. While diverted streams, by definition, have reduced flow, these findings are important because they suggest there are identifiable markers associated with reduced flows within the diverted channels that differ significantly from undiverted channel pairs. On average, the edge-of-vegetation discharge estimates decreased about 26 percent below the diversions in this study, and about 29 percent by frequent-flow estimates. Wesche (1991) reported a 67 percent average decrease in conveyance capacity on low-gradient streams with almost half the flow diverted, but his steeper gradient streams actually showed small increases in estimated discharges. Ryan (1997) also identified both vegetative and geomorphic indications of reduced flows within her low-gradient study channels. Effects of gradient were not apparent in the small diversions of this study, however. We suspect that the use history may be the primary influence at these sites.

Frequent flow and edge of vegetation measure fundamentally different processes. Frequent flow is defined by physical channel features; the edge of vegetation depends on the establishment and survivability of vegetation during the growing season. Frequent flow will be similar above and below diversions where large portions of the annual peaks are allowed to pass, as is common for small diversions. Pronounced changes in channel geometry are often found below large dams and diversions where the annual hydrographs are significantly altered and channel-forming flows are eliminated or reduced. The edge-of-vegetation discharge is more indicative of growing season conditions, and the smaller edge-of-vegetation discharge estimates below diversions appear to indicate vegetative encroachment. Encroachment is of particular interest because it potentially impacts flood conveyance

Table 9—Test of stem densities for layer 1 (0 to 6 inches).

Site	Stems less than1 cm Above	Stems less than1 cm Below	Site	Stems greater than 1 cm Above	Stems greater than 1 cm Below
	- - stems per square ft - -			*- - stems per square ft - -*	
July	10.33	7.71	July	0.21	0.00
Alturas	7.23	5.04	Alturas	.45	.15
Boone	2.06	3.85	Boone	.27	.11
Boulder	.23	.52	Boulder	.10	.12
Cottonwood	1.10	.83	Cottonwood	.47	.09
Eagle	.66	1.30	Eagle	.03	.10
Ethel	2.53	1.55	Ethel	.09	.00
Hawley	2.05	2.16	Hawley	.00	.14
Knapp	2.71	4.99	Knapp	.07	.08
McDevitt	1.15	7.83	McDevitt	.21	.47
Morgan	2.00	4.21	Morgan	.20	.19
North Fork Burnt	1.03	.90	North Fork Burnt	.35	.19
Pole	2.78	3.03	Pole	.00	.00
Valley	1.34	1.74	Valley	.00	.13
Van Horn	1.04	1.52	Van Horn	.25	.04
West Fork Burnt	1.99	.24	West Fork Burnt	.03	.31
Mean	2.52	2.96	Mean	.17	.13
Standard deviation	2.62	2.43	Standard deviation	0.16	.12
P value	0.4080		p value	0.4532	

Table 10—Test of stem densities for layer 2 (6 to 48 inches)

Site	Stems less than1 cm		Site	Stems greater than 1 cm	
	Above	Below		Above	Below
	- - stems per square ft - -			*- - stems per square ft - -*	
July	9.98	7.36	July	0.35	0.00
Alturas	6.23	2.83	Alturas	.22	.03
Boone	3.17	3.26	Boone	.30	.01
Boulder	.59	.35	Boulder	.04	.05
Cottonwood	2.02	1.55	Cottonwood	.75	.43
Eagle	1.06	2.28	Eagle	.01	.45
Ethel	3.37	1.90	Ethel	.09	.00
Hawley	1.04	2.43	Hawley	.05	.00
Knapp	4.32	4.18	Knapp	.05	.00
Mc Devitt	1.23	.90	Mc Devitt	.13	.16
Morgan	2.13	8.99	Morgan	.13	.40
North Fork Burnt River	1.83	1.22	NF	.42	.04
Pole	1.94	1.55	Pole	.00	.00
Valley	1.65	6.12	Valley	.00	.22
Van Horn	1.32	1.41	Van Horn	.25	.00
West Fork Burnt River	1.92	.64	West Fork Burnt River	.02	.38
Mean	2.74	2.93	Mean	.18	.14
Standard deviation	2.40	2.52	Standard deviation	.20	.18
p value	0.4691		p value	0.4532	

Table 11—Test of average stem diameters.

Site	Layer 1 (0-6 inches) Above vs. Below		Layer 1 (0-6 inches) "C" vs. Above		Site	Layer 2 (>6-48 inches) Above vs. Below		Layer 2 (>6-48 inches) "C" vs. Above	
July	1.50	0.00			July	1.65	0.00		
Alturas	5.00	1.67			Alturas	3.22	1.50		
Boone	1.80	1.56			Boone	2.50	1.50		
Boulder	6.16	2.57			Boulder	10.66	2.67		
Cottonwood	7.98	3.75			Cottonwood	6.46	2.61		
Eagle	1.00	2.58			Eagle	2.50	2.23		
Ethel	1.75	.00			Ethel	2.00	.00		
Hawley	.00	1.86	4.00	0.00	Hawley	2.00	.00	3.35	2.00
Knapp	5.23	2.17	1.00	5.23	Knapp	2.85	.00	1.00	2.85
McDevitt	2.31	3.38	2.95	2.31	McDevitt	2.40	4.00	2.13	2.40
Morgan	1.83	1.92			Morgan	2.67	2.17		
North Fork Burnt	3.44	5.07	3.00	3.44	North Fork Burnt	3.08	4.67	2.16	3.08
Pole	.00	.00	1.00	.00	Pole	.00	.00	.00	.00
Valley	.00	2.00	1.00	.00	Valley	.00	1.80	1.80	.00
Van Horn	13.21	3.00			Van Horn	2.50	.00		
West Fork Burnt	3.50	3.08	9.25	3.50	West Fork Burnt	3.50	2.09	100.00	3.50
Mean	3.42	2.16	3.17	2.07	Mean	3.00	1.58	15.78	1.97
Standard deviation	3.50	1.39	2.94	2.12	Standard deviation	2.50	1.50	37.15	1.43
	p value = 0.2051		p value = 0.2359			p value = 0.0213		p value = 0.6715	

by altering the channel's roughness. Channel gradient and response did not appear to be related. In contrast, Wesche (1991) and Ryan (1997) were clear that only low-gradient streams were affected in their studies.

Typically, flow diversion reduced both frequent flow and edge-of-vegetation conveyance estimates. It may be instructive, however, to examine one of the streams that did not follow this general trend. Eagle Creek carries the greatest estimated edge-of-vegetation flow of all the study streams. It is a steep, high-energy stream, and no water was diverted during the spring prior to sampling in the summer of 1993, due to a break in the canal. Eagle Creek is the first of several streams that are fully captured by a common, earthen canal that intersects the stream, so that water must pass through a wooden headgate off the canal to continue flowing downstream. The headgates leak a little even when closed, and are probably fully or partially open during most snowmelt seasons. The estimated edge-of-vegetation flow above the diversion was 175 c.f.s., and flow below was estimated at 176 c.f.s. The frequent flow estimates for Eagle Creek, however, dropped notably (72 c.f.s. above and 56 c.f.s. below), even though steep-gradient, high-energy streams such as Eagle Creek are generally not considered to be alluvial and, therefore, are less susceptible to moderate flow changes and spring runoff passed through the canal prior to sampling. The D_{50} particle size, which would be expected to change if there was a change in stream power, was the same above and below the canal. These results are contrary to data from other study sites, and seem to suggest that there is insufficient discharge below the headgate to maintain the frequent-flow indicators at a high level, but sufficient leakage to support the vegetative community. Because spring 1993 snowmelt flows were allowed to pass downstream, the data may also be evidence that frequent-flow indicators are not necessarily valid in high-gradient streams that are not building floodplains or bars.

Substrate and Sediment Transport

The T-tests of all paired sites for differences in the percent of fine particles in the substrates were nonsignificant. The Chi-square results of substrate differences at each site were often significant, but the number of sites that had significantly more fine particles below and more fines above the diversions was nearly equal (table 5; fig. 8). It appears from these data that, although particle size distributions above and below an individual diversion may differ significantly, they do not differ in a predictable way, and may be within the natural variation of the system. Variation in the diversion structures may also account for the inconsistent results; sediment moves downstream readily during bankfull flows at some sites, but is trapped or diverted by structures at other sites. Interpretation of these data is further complicated by the fact that roughness did not change significantly below diversions, despite reduced conveyance, and typically larger width:depth ratios (table 6). Changes in roughness would be expected if sedimentation occurred due to reduced flows. The study sites at Hawley Creek and Ethel Creek stand out in figures 8 and 9 because they have unusually high percentages of fine particles. The diversion structure at Hawley Creek is an earthen dam blocking the channel and fully capturing the stream for an unlined canal, which then traverses the slope above the dry channel before turning away. During spring runoff, and quite possibly during other times of the year, some streamflow overtops the canal in several places and runs downhill to the channel below the dam. There is also seepage beneath the dam and canal that surfaces below the dam to help supply the trickle of water down the center of the channel. The former streambanks appear trampled and eroded by grazing animals and time. Thus, fine sediment is probably supplied by the eroding banks and overland flow from the canal, but the remnant flow is not enough to transport it.

The streamflow at Ethel Creek is also captured by an unlined canal, but some flow is allowed to pass through a headgate into the channel below during spring runoff, and perhaps at other times as well. The coarsest fraction of the bedload can drop out in the shallow gradient of the canal, but the rest passes through the headgate to the channel below. Because of the reduced flow and somewhat lessened gradient, we can speculate that stream power below the canal is not competent to continue transporting all of the remaining bedload, and the portion that settles there is finer than what originated above. The seepage from the canal and whatever flow leaks through the headgate support a mossy encroachment that also can help filter out sediment. While these are two extreme and somewhat unusual examples, the factor they share in common is a loss of competency due to reduced flows, and this same factor probably exists to a lesser degree at other sites.

Data from Pole Creek suggest how some stream substrates can coarsen below diversions. Figure 11 displays bedload transport rates from Pole Creek on two different dates. On May 17, 1995, all flow remained in the stream channel; the rate of sediment transport above the diversion was somewhat lower than below it (71 g per min above and 197 g per min below). In contrast, when the same streamflow was diverted into the ditch on June 14, 1995, the rate of transport was much greater above the diversion (2,924 g per min above and 1,120 g per min below). The trendlines for bedload transport with open and closed headgates for all measured streams confirm a tendency for higher rates of sediment transport above the point of diversion, but the disparity increases notably when water is shunted into the ditch. These data suggest that some of the finer fraction of bedload may also be shunted down ditches when headgates are open. Suspended sediment samples showed a similar response to headgate position, but the differences were not significant. This interpretation is supported by the Johnson and Smith report (1979) of diversion of sediment in southwestern Idaho. Another possible mechanism of coarsening the "B" substrate is the deposition of sediment in pools created at the point of diversion, above a sill or low dam. Such deposition was observed but not tested.

Vegetation

The scatter of the paired stem densities shown in figure 12 suggests that the natural variation is large, and no vegetation response was detected. The data, however, indicated significantly larger stem diameters above the diversions, raising the question of whether growing conditions for established plants may be more favorable above diversions, but not strongly apparent at this time. We also observed that nearly twice as many "B" data sets had higher densities of small stems in Layer 1 (table 9). Although this was not a statistical difference, it is pronounced enough to warrant further investigation into whether this observation could reflect new growth and encroachment below diversions. The wide range of plant communities represented at the study sites may have confounded statistical analysis, and further research with better stratification is needed. Plant establishment and maintenance is a complex process dependent on several variables such as scour, source of water and depth to water table throughout the growing season, substrate texture, substrate scouring, microclimate changes, and plant reproductive strategies. It is simplistic to expect any uniform response to reduced water flows, whether it be encroachment, retreat, or change in community structure.

Observations from individual study sites help explain some vegetation dynamics at diversion sites. For example, the channel below the diversion at Hawley Creek illustrates vegetation encroachment due to flow diversion. Although the stream is fully captured by an earthen dam at Hawley Creek, some snowmelt escapes from the diversion canal and flows downhill to the channel below the dam. The channel also intersects a small amount of subsurface flow so that a flow of about 1 c.f.s. is maintained in the channel for a distance below the dam during spring and summer. In addition, the D_{50} and D_{84} (table 1) of the lower channel describe a finely textured substrate that can probably hold moisture within a shallow rooting zone. The result is that the former riparian zone is now delineated by skeletons of dead trees, while a new band of riparian forbs about a foot wide lines the trickle of streamflow. We believe that those trees lined a losing stream reach and were fully dependent on the stream. The edge-of-vegetation flow, as estimated from the green line of new forbs, is substantially smaller than estimates from the undiverted part of the channel. The new growth is also reflected by the higher stem density below the dam (table 9,10).

In contrast to Hawley Creek, spring runoff still flows past the diversion at July Creek, but flow is reduced during the growing season. The free passage of high flows allows for sediment transport and scouring of the channel bottom, and the coarse substrate (D_{84} = 230) is less efficient at holding moisture than the substrate at Hawley Creek. The stem density below the diversion, though still strong, is less than the density measured above, and the discharge estimated from the edge of vegetation is larger, suggesting a retreat of the edge of vegetation. It is also interesting that the frequent-flow estimates, which would reflect disturbance from spring flows, are identical for the channel on both sides of the diversion.

Conclusions

Streamflow conveyance estimates below diversions were significantly smaller than estimates from above, indicating that flow reduction due to small diversions leaves discernable indicators in the channel. These indicators are subtle relative to channel changes found below dams, probably because channel-forming flows and sediment apparently are often allowed to pass below many of these small diversions. In contrast with the findings of Ryan (1997) and Wesche (1991) that the effects of reduced flows were only detectable in lower gradient streams, changes in flows did not appear to correlate with stream gradient.

The passage of at least some channel-forming flows probably accounts for the lack of statistical differences in substrate particle sizes and in channel roughness below the study diversions as a whole. Substrates of several individual streams, however, tested coarser or finer below their diversions. It appears that some bedload is diverted into ditches with the streamflow, or possibly settles out just above some diversion structures. Suspended sediment appears to respond the same way, but the differences between open and closed headgates were not significant. Timing of diversion operation and the design of the diversion structures may account for the differences in particle-size distributions.

The response of vegetation to these small diversions was not strong. Stem diameters in Layer 2 (>6 to 48 inches above the ground) were significantly larger above the diversions, which may indicate more favorable conditions. No other vegetation test was statistically significant. Stratification by substrate, season and size of diversion, community type, source of summer water, or other variables may be necessary to evaluate the effects of diversions on stem density and vigor.

Flow estimates at the elevation of an identifiable channel feature are necessary to compare the conveyance of two stream reaches. Flow estimates were computed for elevations of two features in this study: frequent-flow indicators, which approximated bankfull, and the edge of vegetation. The edge of vegetation appears to be a viable alternative to frequent-flow indicators or bankfull for conveyance comparisons. The edge of vegetation may be more reliable than frequent-flow indicators because conveyance estimates of both free-flowing reaches ("A" and "C") also differed when calculated from frequent flow levels. The edge of vegetation also addresses the question of vegetative encroachment into the channel more directly. Encroachment is of particular interest because of its potential impact on channel roughness and flood-flow conveyance. These concepts merit further testing.

It appears that the operation of the small forest stream diversions has not substantially altered most parameters studied. However, the few statistical changes that were detected, coupled with some provoking observations and analyses of individual streams, suggest a trend toward alteration that is not substantially detectable yet. Hydrographs from above and below the points of diversion and historical data are needed to fully evaluate the channel and vegetation responses to reduced flows.

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