The impacts of ski slope development on stream channel morphology in the White River National Forest, Colorado, USA

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ABSTRACT

The combined influence of tree-clearing, road construction, snowmaking, and machine-grading can cause increased flow and sediment loads along streams in or adjacent to commercial ski resorts. These changes to stream channels can increase bank failures, bed material size, pool scour, and, in extreme cases, channel incision. We used field data from the White River National Forest in Colorado, which includes several major ski resorts, to test the hypothesis that ski slope development causes a significant difference in bank stability, undercut banks, fine sediment, wood load, pool residual depth, and particle size (D_{84}) between the ski area project streams and reference streams. We further hypothesize that the changes in a stream are mitigated by the density and type of vegetation growing along the banks. A significant difference is defined as a project stream that is outside the range of variability of the reference streams.

To test these hypotheses, we surveyed channel conditions, channel dimensions, and vegetation along 47 stream reaches (200–300 m in length). Twenty-four of these streams are within ski areas (project streams), either adjacent to or downstream from ski slopes. Twenty-three reference streams with very little to no development in their basins are used to define reference conditions of bank stability, bank undercutting, bank height, wood load, pool residual depth, sediment size, and vegetation structure. A combination of statistical techniques, including Principal Components Analysis and Classification and Regression Tree Analysis, was used to assess the controls on stream channel morphology and to analyze the differences between project and reference streams.

Project streams that are significantly different than reference streams have a combination of a higher percentage of fine sediment, smaller pool residual depth, and higher percentage of unstable banks. The impacted project streams have bed material derived from granitic rocks and a lower density of understory vegetation. These results show the importance of considering vegetative and geologic influences on channel form and processes when assessing impacts of land use change. Roads and machine-grading have the most significant impact on the streams, causing bed fining and pool filling. These data and results will help in revising a forest management plan to provide guidelines for planning and development of ski areas on public lands.

1. Introduction

Development of ski slopes is one type of land use change that affects the hydrology and subsequently alters the geomorphic processes of a watershed (Troendle, 1987; Ryan and Grant, 1991). The impact of ski slope development on stream channels has become a concern for the United States Forest Service (USFS), which is responsible for managing and maintaining the national forest land on which many of the largest ski resorts in the United States are located (J. Potyondy, Hydrologist, Arapahoe–Roosevelt National Forest, personal communication, 2006). Ski slope development includes tree-clearing, road construction, machine-grading, and snowmaking, which can increase peak stream flow and overall water yield, as well as increasing sediment yield. Past studies have focused on the impacts of tree-clearing or forest roads (Wright Water Engineers and Leaf, 1986; Troendle, 1987; Troendle and Olsen, 1994; Wemple et al., 2001; MacDonald and Stednick, 2003), but none have studied the combined multiple impacts of ski slope development on stream channel morphology. This paper investigates the potential impacts of ski slope development on channel morphology using field

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data from 47 channel segments in the Rocky Mountains of central Colorado (Fig. 1).

Each type of development on a ski slope has the potential to cause a different and sometimes contrary response in the drainage basin. Limited studies show the combined effects of ski slope development on drainage basins or stream channels, therefore the hypothesized changes in the channel morphological characteristics are extrapolated from studies that focus on the different components of development; i.e., tree-clearing, road construction, machine-grading, and snowmaking. Furthermore, most of these studies focus on how these changes in a drainage basin affect the hydrology of the basin and are not specific to changes in the stream channel. None of the studies presented below were conducted in ski areas unless specifically noted.

Tree-clearing and road construction in forested drainage basins have been extensively studied in the western United States. Tree-clearing influences the water yield in the stream as well as changing the timing of the peak flow (Troendle and King, 1985; Jones and Grant, 1996; MacDonald and Stednick, 2003; Jones and Post, 2004). The removal of the forest canopy causes a decrease in interception and transpiration in a basin. The decrease in transpiration leads to an increase in storage of water in the soil (MacDonald and Stednick, 2003). These changes can increase the soil moisture content, allowing more water to be available to drain into channels. Discharges are greater on the rising limb of the hydrograph as the snowpack melts and enters a wetter soil (Troendle and Olsen, 1994). Troendle and King (1985) found that removing 50% of the forest cover led to a 23% increase in the peak discharge of Deadhorse Creek, Colorado.

Tree-clearing can also cause increased erosion from logged sites and subsequent increase in sediment yield (Troendle and Olsen, 1994; McGurk et al., 1996; Motha et al., 2003). Harvested areas can contribute up to five times more sediment than undisturbed sites (Motha et al., 2003). The highest contributions, however, often come from ungraveled roads associated with harvested areas during peak flows. Erosion rates in Colorado remained low as long as there was <30% bare soil in a given drainage basin (Gary, 1975; Benavides-Solorio, 2003). Other studies in Colorado have indicated that increased suspended sediment concentration following partial clearcutting comes from within the channel and not from road building or tree-clearing, suggesting that sediment concentration increases because of increased transport capacity associated with a prolonged duration of higher flows (Troendle and Olsen, 1994). Troendle (1982) found that 20 to 30% of the basin has to be cleared of trees before a marked increase in flow occurs.

Compaction of roads leads to an increase in overland flow, interception of subsurface flow, and increased production of fine sediment (Wemple et al., 1996, 2001). Infiltration rates of forest roads may be only 1 mm/h (Luce and Cundy, 1994; MacDonald and Stednick, 2003), whereas the infiltration rate in a mixed conifer forest can be >260 mm/h (Martin and Moody, 2001). Low infiltration rates on roads produce an increase in runoff, which is then more quickly directed to the stream network through waterbars and ditches (Wemple et al., 1996). Roads intercept slower moving subsurface flow through cutbanks and transform this slower moving flow to faster moving runoff (Wemple et al., 1996; MacDonald and Stednick, 2003). Flow routing from forest roads can increase the drainage density of channels by causing channel initiation farther upslope, or by connecting water bars directly to streams (Montgomery, 1994; Wemple et al., 1996). These disturbances in the basin cause an earlier peak flow with an increased magnitude. The increased efficiency of routing the flow also increases the input of sediment to streams (Luce
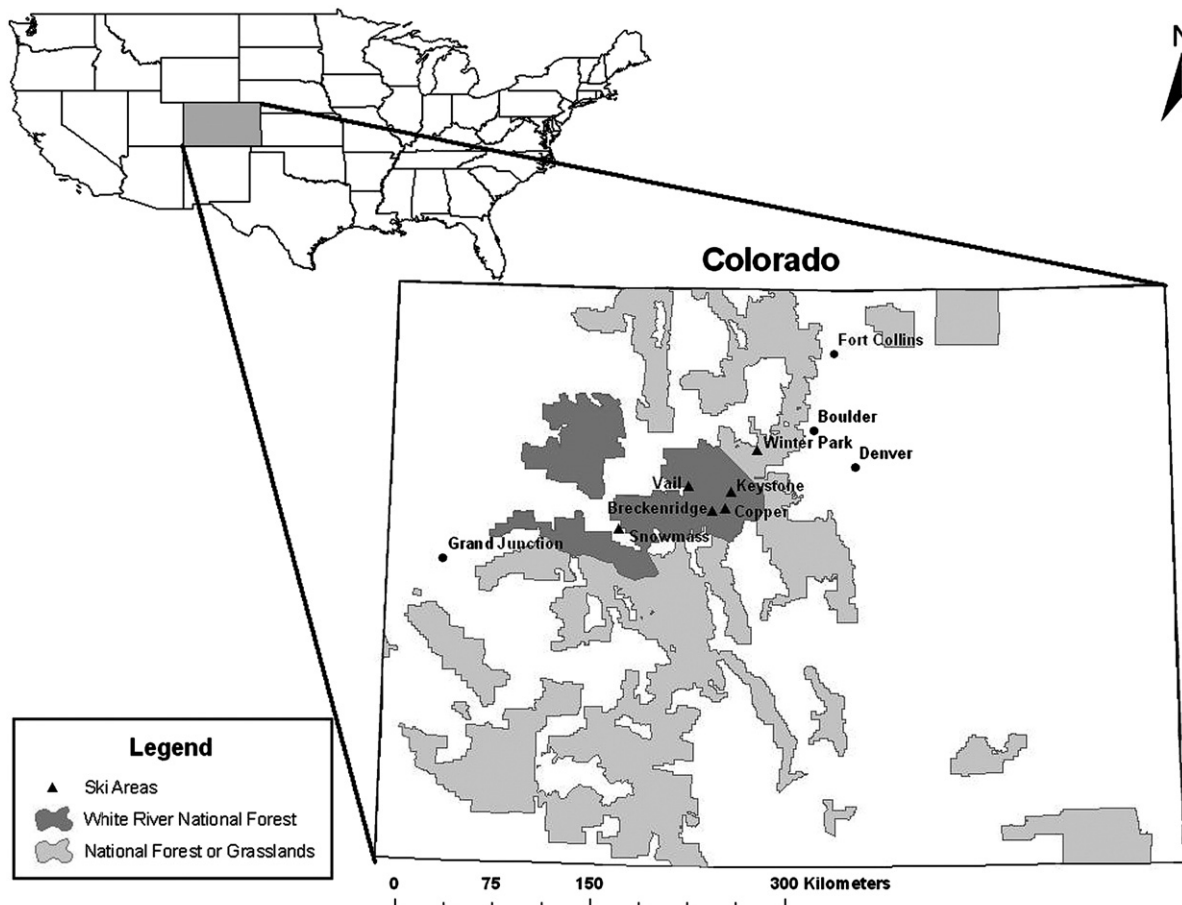

Fig. 1. Location of study sites in White River National Forest, Colorado.

and Black, 1999). Although roads can also intercept and store sediment, roads are predominantly a net source of sediment, mainly from fillslope and cutslope slides (Wemple et al., 2001).

The production of artificial snow on ski slopes can also cause a variety of changes to the hydrology of the basin. Most artificial snow is found on cleared ski runs and is exposed to a greater amount of solar radiation than snow underneath a tree canopy, therefore allowing snowmelt to begin earlier and cause earlier and larger peak flows in streams (Troendle, 1982; Walker, 1998). Alternatively, artificial snow has a higher density than natural snow, which is further increased by compaction on the heavily groomed ski slopes (Wipf et al., 2005). The higher density of the snow can then delay the snowmelt up to four weeks (Keller et al., 2004). Therefore, any change in the timing or volume of the peak flow will depend on the amount of artificial snow, sun exposure and grooming on individual slopes.

Machine-grading of ski slopes is the process of smoothing the slopes by removal of the topsoil, boulders, and vegetation (Ruth-Balaganskaya and Myllynen-Malinen, 2000). In some places, soil is also added to the slopes in a manner similar to that used in roadcuts. The USFS is more concerned with the areas where the topsoil layer is removed completely because of the increased difficulty of revegetating these slopes (M. Weinhold, Forest Hydrologist, White River National Forest, personal communication, 2006). Studies conducted in Europe indicated that machine-grading significantly impacts vegetation and infiltration (Bayfield et al., 1984; Bayfield, 1996; Ruth-Balaganskaya and Myllynen-Malinen, 2000; Wipf et al., 2005). Wipf et al. (2005) found that the percent of ground not covered by vegetation was five times greater on graded versus ungraded ski slopes in the Swiss Alps. This proportion was not affected by revegetation measures or even the time since machine-grading.

The effects of human alterations on a channel depend on hillslope and channel coupling, the sequence of upstream channel types, and local channel morphology (Montgomery and Buffington, 1997). Hillslope and channel coupling occurs when sediment mobilized on the slopes can move directly into the streams (Church, 2002). More closely coupled streams are likely to be more responsive to increases in sediment supply caused by the land use activities described earlier. Stream responsiveness also depends on the stream's ability to transport sediment, as reflected in the distinction between steeper transport segments that are capable of transporting increased sediment supply and have coarse substrate that limits scour associated with higher discharge, and lower-gradient response segments that are more likely to locally aggrade in response to increased sediment (Montgomery and Buffington, 1997). Channel changes occur over various spatial and temporal scales. Increased sediment load in a channel unable to transport that load causes aggradation, channel widening, bed fining, and pool filling (Montgomery and Buffington, 1997; Rathburn and Wohl, 2003). These changes depend on the location of the sediment input, as well as the time since disturbance when the channel is surveyed. The initial increase in sediment load can cause aggradation and pool filling, but if the sediment load eventually decreases again there may be channel incision and pool scour.

Potential channel responses to increased discharge include changes in the width/depth ratio as the channel boundary erodes, changes in grain size and bedform geometry as sediment transport capacity increases, and pool scour or channel incision (Liébault et al., 2002; Marston et al., 2003). Bed incision may occur where cohesive bank material, root reinforcement, or bedrock exposure limit bank erosion (Fonstad, 2003). Increased discharge can also cause greater amounts of undercutting of banks and movement of sediment and wood in the streams (Harr, 1981; Montgomery and Buffington, 1997).

All of these changes in a channel interact in complex ways depending on the type of disturbance, the channel morphological characteristics, and the surrounding vegetation type and density. Expected channel responses to changes in peak flow and water yield include bed coarsening, bank erosion, pool scour, and in extreme cases, channel incision (Knighton, 1998). In each case, a possibility exists that little change will occur in the channel morphology. Stream channels are complex systems, however, and one change often triggers another, causing multiple responses to a single influence (Schumm, 1974). Often, these channel responses negatively impact the riparian habitat and water quality.

1.1. Key research questions

The existing literature indicates the potential for a variety of responses in stream channels as a result of activities commonly undertaken as part of ski slope development. Our study areas are within the steepest portion of the channel network and might be expected to show limited morphological responses to changes in water and sediment yield relative to other portions of the network (Montgomery and Buffington, 1997). Nonetheless, we expected that the effects of ski slope development would be substantial enough to allow us to test the following hypotheses:

H_1. Development of ski slopes will significantly alter the channel morphology of "project" versus reference streams, where project streams are located in basins with ski slope development and reference streams are in otherwise analogous basins with little to no development. The small amount of development in reference basins refers to hiking trails. A significant impact is identified when the characteristics of a project stream are outside the range of variability of the reference streams. We further hypothesize that the type and magnitude of alterations in project streams versus reference streams will depend on local geology and drainage area.

H_2. Changes in each morphological variable (i.e., percent undercut banks, percent unstable banks, percent fine sediment, D_{84}, bankfull width, pool residual depth, and wood) are controlled by the combined interactions among response variables and other channel characteristics, i.e., gradient.

H_3. Channel response to increased discharge and sediment load is mitigated by bank vegetation such that changes in response variables correspond to type and density of bank vegetation.

H_4. The type and magnitude of change of each morphological variable will be a function of type and magnitude of ski slope development; i.e., extent of machine-grading, tree-clearing, road construction, and snowmaking.

By testing these hypotheses, we can explore whether ski slope development has the potential to significantly alter the form and function of adjacent stream channels, and assist the USFS and other management agencies in developing guidelines to mitigate potential impacts.

2. Regional setting

The White River National Forest is located in the Rocky Mountains of Colorado. The small headwater streams (drainage area of 1–15 km^2 at each study site) that are part of this study are located in or near Vail, Copper, Keystone, Breckenridge, Snowmass, and Winter Park ski areas (Fig. 1). Headwater streams chosen for this study are confined, steep gradient, step-pool, and cascade streams because these are the most prevalent types of channel morphology in the vicinity of the ski slopes. The streams have a low width/depth ratio and a low sinuosity. The elevations of the reaches range between 2550 and 3450 m. The vegetation consists mainly of pine (*Pinus contorta, Pinus ponderosa*), spruce (*Picea engelmannii*), fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*) with smaller shrubs, including willows (*Salix monticala, Salix drummondiana*), alders (*Alnus incana*), and currants (*Ribes coloradense, Ribes wolfii*), growing along the stream banks or in wetland areas.

The study sites are located mainly in the Proterozoic Cross Creek granite (granodiorite to granite) and Middle Pennsylvanian Minturn

Formation (a coarse clastic facies and a fine-grained evaporite facies) (Tweto and Lovering, 1977). The streams were divided into catchments underlain by granitic bedrock or sedimentary bedrock (Table 1).

Precipitation patterns in the White River National Forest are controlled mainly by the mountainous topography. The majority of precipitation falls in the form of snow during the winter months. Above 2400 m the snow accumulates, and during spring melt it is the major source of water for the state (Doesken et al., 2003). During summer months, thunderstorms are generated in the mountains (Doesken et al., 2003). Cumulative average annual precipitation is about 56 cm and cumulative average annual snowfall is 470 cm (NOAA, 2006). Each ski resort adds a depth of 20 to 30 cm of snow to the ski runs by snowmaking (M. Weinhold, Forest Hydrologist, White River National Forest, personal communication, 2006). The water for snowmaking is

taken from a river below the ski runs and transported into various basins for snowmaking. Winter Park is the longest running ski resort, having been in operation since 1940; Vail, Breckenridge, and Snowmass opened in the 1960s; Keystone and Copper Mountain in the early 1970s; and Beaver Creek is the youngest resort, having opened in 1980. Snowmaking began at most of these resorts in the late 1960s early 1970s. Breckenridge began its snowmaking in 1981.

3. Materials and methods

3.1. Field methods

Forty-seven stream reaches between 200 and 800 m long were chosen for this project. Twenty-three reference streams are in drainage

Table 1
Summary description of project and reference streams

Name[a]	Geology	Drainage area	Gradient	Reach length	Bankfull width	Pool residual depth	Wood	Unstable banks	Undercut banks	Fine sediment	D_{84}
		(km^2)	(%)	(m)	(m)	(m)	(# pieces/m^2)	(%)	(%)	(%)	(mm)
*Barton North Fork of South Fork	Granitic	2.04	13.5	857	1.6	0.19	0.41	7	76	24	63
*Barton North Fork Reach 2	Granitic	2.53	7.8	812	1.4	0.18	0.22	13	52	31	36
*Barton Middle Fork	Granitic	3.48	5.8	154	1.6	0.17	0.24	1	17	30	28
*Bighorn Reach 2	Granitic	9.62	5.4	495	4.4	0.39	0.06	11	24	12	78
*Booth Creek Reach 2	Sedimentary	15.18	9.0	484	5.8	0.43	0.02	5	10	13	237
*Booth Creek Reach 3	Granitic	10.48	9.8	472	4.6	0.40	0.02	14	14	7	185
*Copper Creek	Sedimentary	3.20	10.4	507	2.0	0.22	0.03	6	62	8	115
*Cucumber Creek Reach 2	Granitic	1.71	10.4	272	2.0	0.19	0.25	10	58	23	86
*Humbug Creek	Sedimentary	3.50	14.1	378	3.4	0.22	0.04	3	52	10	195
*Jacque Creek	Sedimentary	3.53	5.0	515	2.2	0.28	0.03	0	42	23	115
*Jacque Creek Reach 2	Sedimentary	6.59	6.8	235	4.3	0.40	0.03	6	44	7	163
*Jones Gulch Reach 3	Granitic	6.54	10.0	215	3.3	0.22	0.08	15	53	51	95
*Lenawee Reach 1	Granitic	0.75	15.6	341	1.1	0.15	0.07	3	72	33	178
*Lenawee Reach 2	Granitic	3.40	17.1	206	1.9	0.17	0.16	11	78	17	119
*McCoy Gulch Reach 3	Sedimentary	7.14	2.9	173	2.9	0.23	0.02	5	1	19	71
*Meadow Creek Reach 3	Granitic	6.46	10.8	300	3.7	0.29	0.06	4	81	15	154
*Middle Reach 3	Sedimentary	15.35	13.0	661	3.7	0.34	0.04	7	14	18	310
*Middle Reach 4	Sedimentary	15.05	7.1	337	3.3	0.31	0.03	10	12	12	177
*Pitkin Creek	Granitic	13.08	9.0	523	5.1	0.34	0.04	2	29	8	142
*Polk Creek	Sedimentary	4.84	4.5	313	6.1	0.27	0.02	11	29	30	49
*Smith Gulch	Sedimentary	2.60	7.7	349	1.8	0.19	0.03	5	52	13	166
*South Barton Gulch	Granitic	2.19	11.5	300	2.6	0.18	0.14	11	61	19	85
*West Willow Creek	Sedimentary	2.74	9.4	254	3.6	0.23	0.01	26	17	83	133
Beaver Base Creek	Sedimentary	1.21	9.5	244	1.3	0.10	0.17	30	55	41	39
Camp Creek Reach 1	Granitic	2.70	21.5	180	2.5	0.20	0.06	46	79	19	128
Camp Creek Reach 2	Granitic	1.55	21.2	123	1.4	0.13	0.18	13	77	50	27
Cucumber Creek South Fork	Granitic	1.34	16.3	241	1.4	0.13	0.16	0	77	78	9
Earls Bowl	Sedimentary	3.83	7.8	316	1.9	0.18	0.05	2	60	58	56
East Brush	Sedimentary	5.65	10.0	314	3.2	0.27	0.02	5	49	15	205
Game Creek Reach 3	Sedimentary	8.40	3.9	314	2.8	0.23	0.05	8	50	43	53
Jones Gulch (Breckenridge)	Granitic	1.43	8.9	361	1.8	0.11	0.06	12	62	24	92
Jones Gulch Reach 1 (Keystone)	Granitic	7.01	10.8	333	2.0	0.22	0.11	5	95	17	147
Keystone Gulch	Granitic	2.99	5.2	746	1.7	0.21	0.04	0	69	45	37
Lehman Gulch	Granitic	2.63	10.2	403	1.6	0.19	0.02	6	60	16	63
Little Vasquez Creek	Granitic	9.91	8.3	305	3.1	0.22	0.05	43	48	5	180
McKenzie Gulch	Sedimentary	1.12	23.2	189	1.7	0.23	0.13	7	50	13	121
Mary Jane Creek	Granitic	1.07	10.0	269	1.8	0.17	0.27	23	36	54	77
Mozart Gulch	Granitic	3.61	11.8	500	1.7	0.19	0.21	7	76	20	83
North East Bowl (Mill Creek)	Sedimentary	2.83	14.2	208	1.4	0.13	0.47	11	28	66	56
Outback Gulch	Granitic	4.72	7.0	459	2.0	0.24	0.05	2	71	51	74
Parsenn Creek	Granitic	1.89	8.5	205	3.0	0.19	0.07	1	29	41	88
Sawmill Gulch	Granitic	5.74	8.5	353	2.7	0.29	0.11	20	47	15	51
Stone Creek Reach 2	Sedimentary	7.41	14.3	220	2.7	0.29	0.05	4	47	16	149
Union Gulch	Sedimentary	3.22	11.8	581	2.3	0.24	0.02	11	59	8	124
Wheeler Reach 1	Sedimentary	3.92	11.3	301	2.9	0.30	0.11	19	61	23	148
Wheeler Reach 2	Sedimentary	1.97	7.3	403	1.7	0.22	0.06	1	58	27	96
Wheeler Reach 3	Sedimentary	2.21	14.7	203	2.9	0.24	0.09	19	48	23	126

[a] Project streams are marked with an asterisk; reference streams in bold.

basins with little to no development. Twenty-four project streams are located in drainage basins with development ranging from 1.5 to 60% of the basin area cleared of trees. The basins with a small percentage area cleared of trees are considered developed because of the combination of snowmaking in the basin and disturbed areas connected to the stream via waterbars. The stream reaches were initially chosen with the aid of a Geographic Information System (GIS). Thirty-meter DEMs were used from the USDA Forest Service Geometronics Service Center in 7.5-min quad format. To reduce variability between and within a reach, reaches were chosen based on similar aspect, gradient, elevation, geology, and vegetation. These restrictions caused reach lengths to vary between 200 and 800 m. Also, after the USFS conducted initial surveys, they determined that a reach length of 200 to 300 m was enough to characterize the stream.

Stream survey methods were based on the White River National Forest Service Protocol (Overton et al., 1997; USFS, 2003). Each reach was separated into subreaches of glide runs, riffles, pools, cascades, and waterfalls. Culverts, backwaters, and dry channels were also classified as subreaches. Pools were visually identified as scour pool, lateral pool, plunge pool, dam pool, or step-pool complex. Step-pool complexes were identified based on the presence of three or more qualifying pools with steps shorter than the average wetted width between them. A lateral pool is defined as a pool that occurs at a bend between riffle sections. A plunge pool occurred at the bottom of a step. Dam pools were most often found upstream of a wood jam, and scour pools were areas in the center of the channel that had been scoured to create a pool.

To classify each subreach as a separate unit, the main criteria were that it must be longer than wide and be distinct from the surrounding area. Cascades, riffles, and glide runs were classified based on the gradient of the unit: 9%, 2–9%, and 2%, respectively. Pools were classified as such if they were bound by a distinct head crest and tail crest, the thalweg ran through the pool, the profile was concave, and maximum pool depth was at least 1.5 times the tail crest depth. For all pools, the maximum tail crest depth, maximum pool depth, and average depth were measured. The following methodology was used to measure the average depth: (i) The average of the maximum pool depth and tail crest depth was determined in the field and the new calculated depth located in the pool. (ii) Four measurements of depth were made along a cross section perpendicular to the thalweg and then averaged.

For each subreach, the following variables were measured: gradient (S), bankfull width (w_b), wetted width (w), length of unstable banks, length of undercut banks, maximum depth of undercut banks, average depth at bankfull (d), number of pieces and size class of instream wood, adjacent vegetation type and size class, and adjacent land use. Gradient was measured using a transect tape and clinometer. The criteria used to define w_b were a break in slope and change in vegetation type. We assume that w_b reflects the magnitude of the average annual peak flow. Waterfall subreaches were too dangerous to survey and therefore were noted as present but excluded from the survey.

Banks were determined to be unstable if there was active erosion on the banks or visible fractures, indicating that failure was imminent. Any banks that had failed but were revegetated at the time of the survey were not counted as unstable. The length of unstable banks was determined for both banks and then used to calculate the average percentage of unstable banks for each stream. The length of the horizontal undercut of banks was also measured to the nearest 0.1 m on either side of the subreach and used to calculate the percentage of undercut for each stream. Banks were undercut if the horizontal length of bank undercut was >5 cm.

Instream wood was classified as single pieces, aggregates, or rootwads. The minimum size of wood pieces was >two-thirds wetted width and ≥10 cm diameter at breast height. Aggregates included wood that had two or more qualifying pieces touching (Overton et al., 1997; USFS, 2003). The number of qualifying pieces was counted for

each aggregate. Rootwads included pieces that had only the roots of a tree with no trunk in the stream. These data were used to determine the number of pieces of wood per square meter of channel. Because the size of wood pieces was not measured, we did not calculate volume of wood.

Pool/riffle ratio was calculated for each stream and pebble counts were conducted in an equivalent proportion of pools and riffles using a modified version of the Wolman (1954) pebble count. Pebble counts were conducted in the active channel using a 260×260 mm sampling frame placed along a transect in a pool tail-out or riffle perpendicular to the thalweg, and measuring clasts under the crosshairs of the sampling frame. Following USFS protocol, 150 pebbles were counted in project streams and 300 in reference streams. Reference streams had a greater number of pebbles counted to increase the accuracy of the characterization of these reaches.

A vegetation survey began at the downstream end of each reach and proceeded upstream. Streams were divided into blocks measuring 10 m by one channel width. Vegetation was surveyed in a 10-m block from the stream edge to bankfull and then a second block from bankfull to one channel width. Vegetation was stratified into overstory vegetation >5 m in height, understory, and ground cover of herbaceous vegetation. Within each block, vegetation was categorized based on percent cover classes of 0–1%, 1–5%, 5–10%, 10–25%, 25–50%, 50–75%, and 75–100%. Vegetation type in each category was recorded along with the cover class. The type was recorded in order of dominance for each percent cover class in each plot.

We measured drainage area (A) and land use data using a Geographic Information System (GIS). Buffers were used to find the area that was cleared of trees and the slopes that were graded within 15, 30, and 90 m of the stream. Increase in drainage density was determined by measuring the stream length and length of connected roads in each basin using a combination of aerial photographs, 30-m DEM, and field surveys. Increase in drainage density, calculated as a percentage, was the drainage density of streams with connected roads relative to the drainage density of the undeveloped basin without these features.

Increase in peak flow and increase in water yield relative to the absence of ski slope development were found using a combination of data from GIS, the model developed by Wright Water Engineers and Leaf (1986) for calculating peak flow, and water yield and modeling in WRENSS (Water Resources Evaluation of Non-Point Silvicultural Sources) to compare before-and-after ski slope development hydrographs (USEPA, 1980). USFS hydrologists computed the increase in yield and peak flow in WRENSS and provided the data for use in the analysis.

3.2. Statistical methods

A combination of Cluster analysis, Principal Components Analysis (PCA), Classification and Regression Tree (CART), Analysis of Variance (ANOVA), Analysis of Covariance (ANCOVA), best subsets regressions, and Analysis of Similarity (ANOSIM) were used to identify significant trends in the data set and to formally test our hypotheses. SAS/STAT (SAS Institute Inc, 2006) and Multivariate Statistical Package (MVSP) (Kovach Computing System, 2002) were used for all statistical analyses except CART and ANOSIM. CART Decision Tree Software ver. 6.2 was used to conduct CART analyses (Salford Systems Inc., 2006; SAS Institute Inc., 2006). Primer ver. 6 was used to perform ANOSIM (Clarke and Gorley, 2006).

Means of continuous variables were compared between classes using ANOVA. An ANCOVA model combines both an ANOVA and regression for continuous variables, or covariates, which allows for tests of differences between groups once the effects of the continuous variables are taken into account. This analysis assumes that the continuous independent variable is significantly related to the dependent variable and that the significance does not change between groups/categories. The null hypothesis is that the response variable is not significantly different between groups.

A best subset regression is a method of selecting a model by computing all the possibilities contained in the data set and outputting the best models. We used both the Mallow's C_p and adjusted R^2 to determine which model was the most suitable. The C_p is calculated by comparing a reduced model to a model with all the variables. The minimum C_p is sought to determine the best model by finding the model with the smallest mean squared error and the smallest bias (Kutner et al., 2005). The adjusted R^2 is adjusted for the number of variables in the model. The maximum adjusted R^2 is used for model selection. All variables that we hypothesized had an influence on the channel morphology were included in each test. Therefore, the significant basin, channel, vegetation, and development variables were all included. Best subset regressions were used to find the variables significant at the level of $\alpha = 0.05$.

We evaluated similarities in morphological characteristics between factors (i.e. project/reference, sedimentary/granitic, and vegetation clusters) using ANOSIM, which is broadly analogous to ANOVA. Within and between group morphologic similarity tests are conducted, in this case inter- versus intragroup similarities are formally tested and compared to randomly assigned groups (999 permutations). Tests for differences between groups are conducted through calculating an R statistic (which ranges from −1 to 1) and through calculating a p value from permutations of randomly assigned groups. $R = 1$ indicates complete differences in morphological characteristics between groups and $R = 0$ indicates no difference between groups (negative R indicates that similarities between groups are greater than within a group). p values are from a permutation test of the null hypothesis of no difference between groups. Bray-Curtis similarity matrices were used in ANOSIM analyses.

A cluster analysis is a method used to find structure in a multivariate data set (Jongman et al., 1995). The Proc Fastclus procedure was used in SAS to cluster these data. This procedure uses a method called nearest centroid sorting (SAS Institute Inc., 2006). The clusters are based on Euclidean distances between data points. The Fastclus procedure begins by assigning initial cluster seeds as first guesses of the means of the clusters. Each of the data points is then assigned to the nearest seed to form temporary clusters. The means of the temporary clusters are found and the seeds are replaced by these means. The process is then repeated until the clusters do not change. In k-means regression, the number of clusters must be specified.

Ordination is a useful method of extracting dominant patterns from an infinite number of options. PCA is an ordination technique that rearranges the data into a smaller set of composite variables (McCune and Grace, 2002). This method fits straight lines through the data to minimize the total residual sum of squares. The greatest amount of variation in the data set is found in the first few principal components, which is reflected in the eigenvalues for each principal component. The data points are then projected onto the best-fit line to find the first "principal component". Eigenvalues represent some portion of the original total variance (McCune and Grace, 2002). MVSP (Multivariate Statistical Package) was used to conduct PCA analyses (Kovach Computing System, 2002).

PCA provided a descriptive tool for categorizing the distribution of vegetation along each reach. The PCA axis scores describe the vegetation cover along each reach and were used in the ANCOVA models to represent the type and density of vegetation along each channel reach. The complete results of the PCA are presented in David (2007). The PCA axis scores used in the ANCOVA models are described in Table 2.

CART is another method of dividing the data set into similar groups and identifying which variables make each of these groups alike. This is a nonparametric method, which rectifies some of the issues of normality that are an issue in the parametric methods (McCune and Grace, 2002). The CART software used here (Salford Systems Inc., 2006; SAS Institute Inc., 2006) divides the data set recursively into increasingly homogeneous subsets.

Table 2
Variables names and descriptions

Variable names		Variable descriptions
Basin	Stream type	Categorical variable that indicates if stream is a project or reference stream
	Geology	Categorical variable that indicates if the stream is in a granitic or sedimentary lithology
Channel Characteristics	Drainage area A	The area of the drainage basin (km²)
	Gradient S	Slope of reach (%)
	Fine sediment	Sediment <6 mm (%)
	D_{84}	84th percentile grain size (mm)
	D_{84mod}	$D_{84mod} = \dfrac{D_{84}(m)}{\sqrt{\text{Drainage area}(m^2) \cdot \text{gradient}}}$
	Undercut banks	The percent of undercut banks
	$Bwmod$	$Bwmod = \dfrac{\text{Average bankfull width}(m)}{\sqrt{\text{Drainage area}(m^2)}}$
	Unstable banks	The percent of unstable banks
	Wood	Number of pieces per m² of stream
	Pool residual depth	Average depth of pools in reach (depth = maximum pool depth − tail crest depth)
	$Poolmod$	$Poolmod = \dfrac{\text{Average pool residual depth}(m)}{\sqrt{\text{Drainage area}(m^2)}}$
Vegetation	Vegetation clusters 1, 2, 3	1 = dominated by spruce overstory and understory; 2 = dominated by willow and alder; 3 = dominated by gramminoids and moss and mixture of willow understory with serviceberry, mountain mahogany and shrubby cinquefoil
	PCA1BKFL	Principal component axis 1 scores for all vegetation above[a] bankfull width = dominated by understory of willow, understory spruce, alder, gramminoids, and overstory spruce significant along this axis
	PCA2OBKFL	Principal component axis 2 scores for overstory vegetation above bankfull width = dominated by alder and lodgepole pine, also significant are aspen, willow and negatively correlated to spruce
	PCA1SE	Principal component axis 1 scores for all vegetation below[b] bankfull width = dominated by understory of willow, also significant are gramminoids
	PCA1UBKFL	Principal component axis 1 scores for understory vegetation above bankfull width = dominated by willow, also significant are spruce and alder
	PCA2UBKFL	Principal component axis 2 scores for understory vegetation above bankfull width = dominated by spruce, also common gooseberry and alder significant along this axis
	PCA1USE	Principal component axis 2 scores for understory vegetation below bankfull width = dominated by willow, also significant are alder and spruce
Development	Grading 15, 30, 90[c]	Percent area graded within 15, 30, or 90 m of stream (range 0 to 25%)
	Cleared 15, 30, 90[c]	Percent area cleared of trees within 15, 30, or 90 m of stream (range 1.5 to 60%)
	Drainage density increase	Percent increase in drainage density from addition of road ditches to stream network (range 0 to 236%)
	Graded density	Density of graded area within the drainage basin (range 0 to 0.25 km²/km²)
	Yield increase	Percent increase in yield from snowmaking and tree-clearing (range 0 to 211% increase)
	Snowmaking	Cubic meters of snowmaking (=depth × area of basin) (range 0 to 280,000 m³)
	Cleared	Percent of basin cleared of trees (range 1.5 to 60%)

[a] Above bankfull width indicates the vegetation between bankfull and one channel width away from the stream.
[b] Below bankfull width indicates the vegetation growing between the water edge to bankfull width.
[c] The percent area graded/cleared of trees from 15, 30 or 90 m away from the stream was initially treated as separate categories. The statistical analysis found that these variables are collinear, so only one was used to represent all three categories.

This type of classification tree, which is based on a categorical variable being used as the dependent variable, was used in the following analyses. CART is used to classify the project and reference streams based on the response variables for a better understanding of how channel morphology represents these groups. A tenfold cross-validation was used for all the CART analysis.

Three response variables were modified to eliminate the apparent cross-correlations that exist with A and S (Fig. 2). Bankfull width and pool residual depth were found to be significantly related to A. D_{84} is significantly related to A and S. Because these are not the relationships of most interest, new variables were created by dividing the variable by A and in some cases S. The final list of variables used in statistical analyses is presented in Table 2.

4. Results

4.1. Basin controls and channel response (H₁)

The ANCOVA models indicate that there are significant differences between project and reference streams for all morphologic variables except for wood (Table 3). The results from the ANOSIM indicate that the morphologic variables that best describe project versus reference streams are the percent of fine sediment, undercut banks, and unstable banks (Fig. 3). Project streams have a higher percentage of unstable banks, fine sediment, and undercut banks than reference streams (Fig. 3). Fig. 3 indicates that there is only a slight difference between the means of percent unstable banks for project and reference streams, but that the range of bank stability is much larger for project streams.

The same three morphologic variables were also found to be significantly different for streams categorized as being underlain by sedimentary versus granitic lithology. Fig. 3 indicates that streams in soils derived from granitic bedrock have a higher percentage of unstable banks, fine sediment, and undercut banks.

A CART analysis was used by creating a decision tree for the two categories of project and reference streams using only the channel characteristics (Table 2). The CART analysis, presented in detail in David (2007), shows that the percent of undercut banks is a significant explanatory variable for classifying project versus reference streams. Figs. 3 and 4 show that all the project streams have >29% undercut banks. This cutoff was the first used by the CART analysis to categorize project and reference streams. The next two categories that the CART analysis used to categorize project streams are the percentage of fine sediment and unstable banks. Fig. 4 shows the values that were used by CART to categorize project versus reference streams. The

percentage of undercut banks in all the project streams is >29%, and a subset of project streams has >16% unstable banks. West Willow Creek is an outlier in this case and was found to be an outlier in many of the statistical tests. Except for a couple of outliers, the majority of the reference streams have 8–35% fine sediment, whereas the project streams have a greater range of percentage of fine sediment.

The ANCOVA model for unstable banks indicates that the percentage of unstable banks increases in reference streams. Fig. 3 shows how close the means are for the two categories with regard to percentage of unstable banks. The range is larger for project versus reference streams. Fig. 4 shows that there is a small subset of project streams with >16% unstable banks, but that there are no reference streams (except West Willow) above this cutoff. The closeness of the means for the two categories explains the confusion of the ANCOVA model. The CART analysis indicates that a subset of project streams and even a subset of reference streams exist outside the range of variability of the main grouping of streams.

The combination of these statistical tests supports hypothesis one (H₁) and allows us to reject the null hypothesis that project and reference streams are not significantly different. In summary, the ANCOVA, CART, and ANOSIM support the interpretation that (i) a significant difference in channel morphology exists for project and reference streams and (ii) the log transformed percent fine sediment, log transformed percent unstable banks, and percent undercut banks are the dependent variables that differ the most significantly between project and reference streams, with project streams having greater percentages of fine sediment, unstable banks, and undercut banks. The ANCOVA models (Table 3) show that the other channel morphologic variables differ as well, but the variation is not as great.

4.2. Channel controls and channel response (H₂)

All the channel morphologic variables that were tested are presented in Table 3. A "0" indicates variables that were tested but found to be not significantly related to changes in each model. A positive or negative sign shows that the correlation between the independent variable and dependent variable is a significant increase or decrease, respectively. A single, double, or triple positive or negative sign indicates the relative
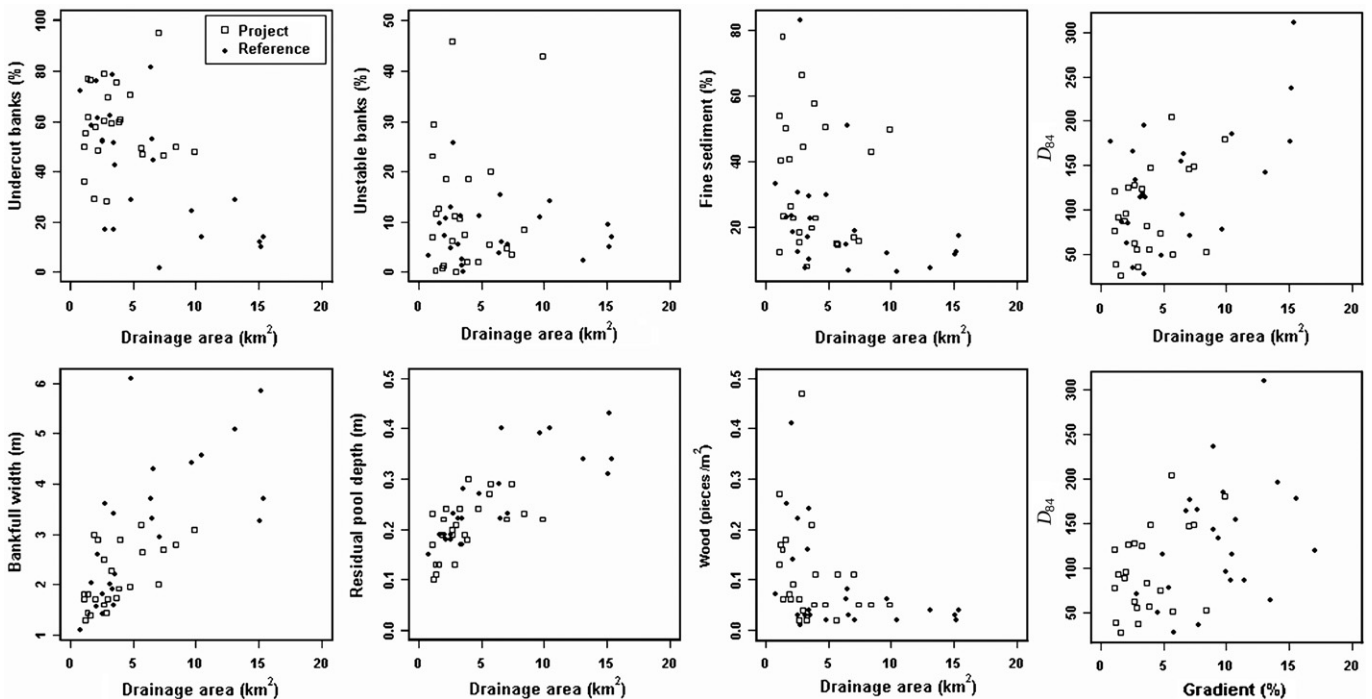

Fig. 2. Scatter plots showing project (squares) and reference (black dots) streams plotted against drainage area for each morphologic variable described in Table 2 and tested in Table 3.

Table 3
ANCOVA models showing relationship of channel morphology to significant independent variables

Independent variables		Dependent variables[a]						
		Undercut banks (%)	Unstable banks[b] (%)	Fine sediment[b] (%)	D_{84mod}[c,d]	BWmod[c]	Poolmod[c]	Wood (# pieces/m²)
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Basin	Reference stream	– –	+	– –	+ +	+	+ + +	0
	Granitic geology	+ +	0	0	– –	0	0	0
	A (m²)	–	+	0				0
Channel	S (%)	0	0	–		0	0	0
	Fine sediment (%)						0	
	D_{84} (mm)	+	0			0	0	
	Unstable banks (%)	0		0		0		0
	Undercut banks (%)		0	0	0	0		0
	w_b^2		0					
	Wood (# pieces/m²)	0	0	+ +	– – –	– –	0	
Vegetation	PCA1BKFL	0	+	–	0	0	0	0
	PCA2OBKFL	0	0	0	0	0	0	+ +
	PCA1SE	0	–	0	0	0	0	0
	PCA1UBKFL	0	0	0	0	0	0	–
	PCA2UBKFL	0	0	0	–	0	–	0
	PCA1USE	0	0	0	0	–	0	0
Development	Grading 15, 30, 90 m (%)	0		0	0	0	0	0
	Cleared 15, 30, 90 m (%)	–	0	0	0	+	0	+ +
	Drainage density increase (%)	0	0	0	+	0	+	0
	Graded density (km²/km²)	+ + +	+ + +	0	0	0	0	0
	Yield increase (%)	0	0	0	0	0	–	–
	Snowmaking	0	0	0	0	0	0	0
	Cleared (% out of whole basin)	0	0	0	0	0	0	0
Model statistics	R^2	0.63	0.39	0.37	0.55	0.29	0.39	0.43
	Adjusted R^2	0.59	0.32	0.29	0.49	0.23	0.33	0.36
	Mallow's C_p	6.17	3.34	4.11	1.37	−2.99	−0.57	3.20
	p-value	0.0001	0.0007	0.02	0.0001	0.0009	0.0001	0.0003

[a] A + indicates a significant increase and − indicates a significant decrease. These variables are all significant at the $p<0.05$ level. The variables with a 0 were included in the best subsets regression and found to be not significant. Additional + or − signs are to show influence of variables relative to other independent variables in the model.
[b] These variables have been log transformed.
[c] These variables have been modified. The calculations of the modified variables are shown in Table 2.
[d] Lenawee Reach 1 removed as outlier.

influence of that variable to the other significant variables based on the parameter estimate for each variable. For instance, for unstable banks an increase in graded density causes a greater increase in the percent of unstable banks than any of the other significant variables.

Wood was an explanatory variable that was significant in three out of the seven models. The D_{84} and S were significantly related to the percent undercut banks and percent fine sediment, respectively. The significance of these morphologic variables supports hypothesis two (H₂) for four of the seven statistical models: percent undercut banks, percent fine sediment, D_{84mod}, and BWmod. The null hypothesis that channel morphologic variables do not influence other morphologic variables is rejected for these models.

4.3. Vegetation controls and channel response (H₃)

The PCA axis scores are used in place of individual vegetation types to describe the overall composition of vegetation along the stream channel. The significant vegetation covers along each of the PCA axes are described fully in Table 2. The results of the ANCOVA models support H₃ by showing that at least one vegetation variable is a significant explanatory variable in all but one model. The percent of undercut banks are not shown to be influenced by any of the vegetation variables.

A cluster analysis was used to categorize streams into three groups based on the three significant morphologic variables discussed under H₁ and shown in Fig. 4; i.e., percent undercut banks, unstable banks, and fine sediment. A decision tree was created using these three categories and the following independent variables: A, geology, S, vegetation. One category in the cluster analysis included the same subset of project streams that can be observed in Fig. 4. The CART analysis revealed that these project streams have smaller A, granitic bedrock, larger S, and a greater amount of spruce/fir overstory; i.e.,

small amount of willow understory. In other words, project streams with high percentages of undercut and unstable banks and fine sediment are more likely to be high gradient segments underlain by granitic geology and vegetated with a high spruce overstory cover.

The CART analysis, in combination with the ANCOVA models, supports the hypothesis that bank vegetation mediates changes in channel morphology (Thorne, 1990; Huang and Nanson, 1998; Abernethy and Rutherfurd, 2000; Gurnell et al., 2002; Rutherfurd and Grove, 2004; Pollen and Simon, 2005). The CART analysis indicates that a subset of streams is more sensitive to development of ski slopes. Project streams with a steeper gradient, in granitic material, and with a thicker spruce/fir overstory are found to be outside the range of variability of the reference streams.

4.4. Development and channel response (H₄)

The ANCOVA models presented in Table 3 also tested the significance of seven separate ski slope development explanatory variables on the dependent morphologic variables. A range of development variables were found to be significant, depending on the model. The graded density was found to have a significantly large influence on the percent of unstable banks and percent undercut banks. Hypothesis four (H₄) is supported for six out of the seven statistical models (Table 3). For these models, the null hypothesis that development does not influence the type and magnitude of change for each morphologic variable is rejected.

5. Discussion

Complex interactions among stream flow, sediment load, topography, geology, and vegetation influence the form and function of mountain streams. Although previous studies have shown how changes

in basin hydrology and geomorphology can influence stream flow and sediment yield, this study has focused on the actual changes observed in stream channels. The statistical analyses show that there are significant differences between project and reference streams. The CART analysis indicates that S, bedrock geology, and vegetation influence what changes occur in project streams. Streams in a granitic material, with steeper gradients and a spruce overstory, are more sensitive to alterations in basin hydrology.

An increase in water yield and peak flow in streams is expected in a basin that has been cleared of trees (Troendle and King, 1985; MacDonald and Stednick, 2003). Machine-grading will cause an increase in runoff from decreased infiltration and increased sediment load from the poorly vegetated slopes (Bayfield, 1996; Wipf et al., 2005). Streams with roads connected directly to them via water bars have an increased drainage density and therefore an increase in the timing and magnitude of the peak flow (Troendle, 1982; MacDonald and Stednick, 2003). Forest roads have very low infiltration capacities compared to forests and are important in increasing the amount of fine sediment found in the streams (Wemple et al., 1996; Luce and Black, 1999; Wemple et al., 2001). The process of snow-making can also increase the water yield in a stream (Wright Water Engineers and Leaf, 1986). We undertook a comparison of ski area streams and streams with little or no disturbance in the basins to further our understanding of how these changes influence streams.

In simplified terms, the response observed in the stream channel depends on the transport capacity versus the sediment supply (Montgomery and Buffington, 1997). The transport capacity depends on the stream flow and channel type (Montgomery and Buffington, 1997). The interactions among variables influencing stream response (together with changes in the basin hydrology) are complex, so it is not surprising that changes in the response variables in the stream channel are sometimes difficult to distinguish. The response of the stream

channels can be discussed in terms of (i) effects of bedrock geology on channel morphology (5.1), (ii) effects of channel controls on channel morphology (5.2), (iii) effects of vegetation type and density on channel morphology (5.3), and (iv) impacts of various types of ski slope development on channel morphology (5.4).

5.1. Basin controls and channel response

Geology is significantly related to D_{84mod} and the percent of undercut banks. D_{84mod} is smaller where igneous and metamorphic bedrock are present. We expected material from sedimentary rocks to correspond to finer sediment in the channel, but the relationship here is more complex. The finer material from sedimentary rocks, such as silts and clays, is more cohesive and therefore more resistant to stream erosion. The sands and gravel that are produced from granitic material are therefore much more easily transported.

Geology is also significant in predicting the percent of undercut banks in a given stream. Table 3 shows an increase in the percent of undercut banks for bed material with a granitic origin versus a sedimentary origin. Again, the silt and clay weathered from sedimentary rocks increases the cohesiveness of the banks (Fonstad, 2003; Anderson et al., 2004), so banks composed of granitic sands and gravels are more readily eroded. Percent undercut is not directly related to the D_{84mod}; there is a relationship with increased percent undercut and decreased size of bed material (Davis and Gregory, 1994; Rutherfurd and Grove, 2004).

5.2. Channel controls and channel response

The percent undercut banks is significantly greater for streams with larger D_{84}. This differs from the relationship between undercut
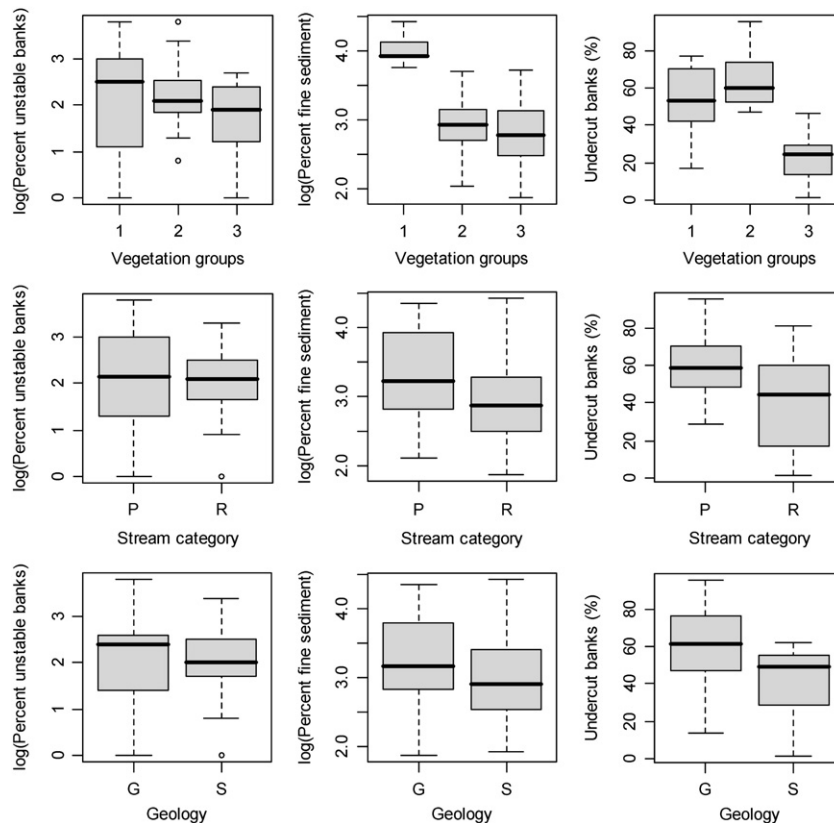

Fig. 3. Boxplots for each categorical variable against the three significant morphologic variables found from ANOSIM results. The vegetation groups were created from a cluster analysis of vegetation. The description of each cluster can be found in Table 2. The results from the ANOSIM show that clusters 1 and 3 are significantly different from each other ($R = 0.32$, p value < 0.001). For stream categories, P is for project and R is for reference streams ($R = 0.08$, p value < 0.005). For geology, G is for granitic and S is for sedimentary ($R = 0.049$, p value < 0.03).
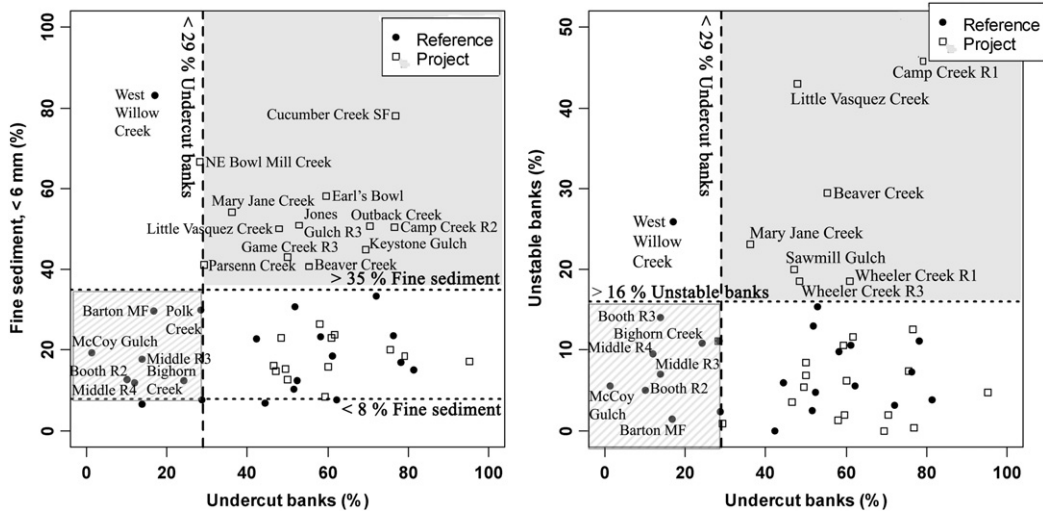
Fig. 4. Threshold values of response variables found using the CART analysis. The square with diagonal lines shows an area that has only reference streams, the light grey contains only project streams and the white square contains a mixture.

and the D_{84mod} variable. The process of interest here is how the roughness elements in the stream influence the amount of undercut banks. The percent of undercut banks was not significantly related to wood or to vegetative cover, unlike previous studies (Davis and Gregory, 1994). Fig. 5 shows two project streams and two reference streams in different lithologies and the height of the undercut banks for each of these streams. In both cases, the height is greater in the granitic streams and in the project streams. The increased height of the undercut could be related to a larger D_{84} that causes shearing to occur higher up on the banks by increasing the height of the zero

velocity plane. Camp Creek is an incised channel, and the height of the undercut is also related to the degree of incision.

The results of the ANCOVA models show that the channel controls on increase in fine sediment include wood and S (Table 3). Wood load is significantly related to an increase in fine sediment and a decrease in the D_{84mod}. Wood in a stream channel increases roughness, creates complex flow patterns, accumulates sediment upstream, and impacts channel form (Montgomery and Buffington, 1997; Buffington and Montgomery, 1999a; Wohl, 2000; Gurnell et al., 2002). Buffington and Montgomery (1999a) found that increased hydraulic roughness from
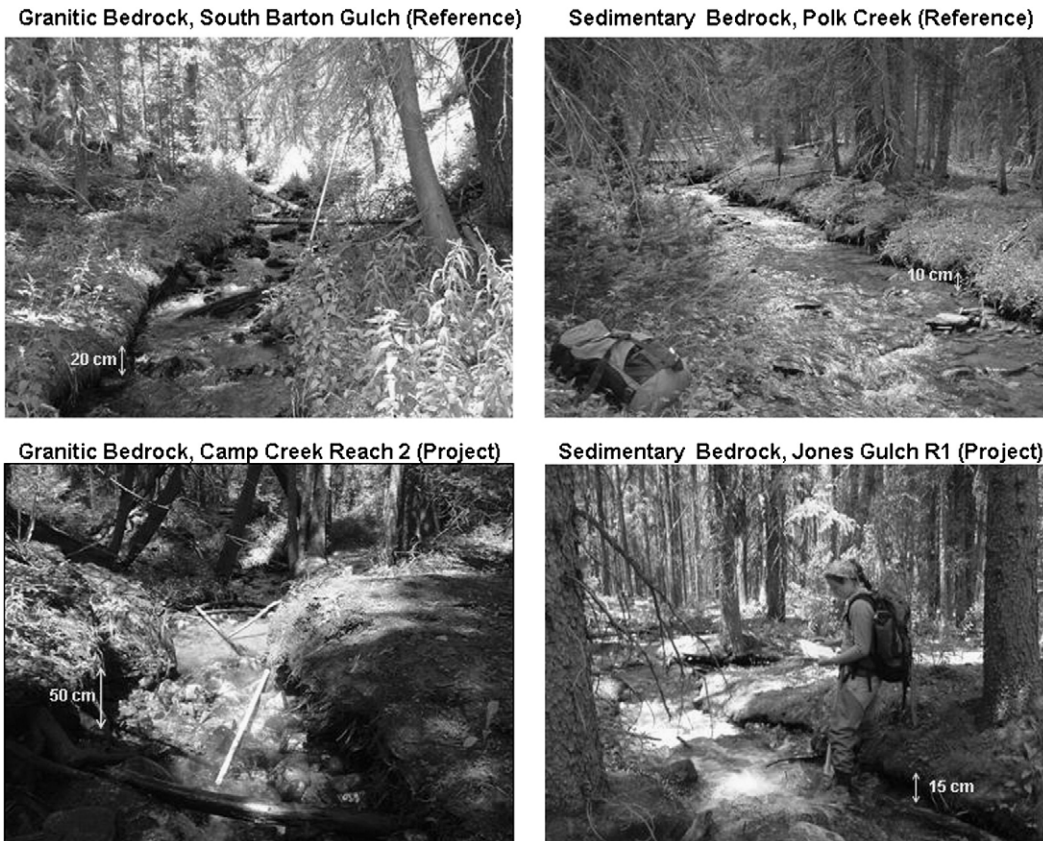

Fig. 5. Comparison of undercut banks in project and reference streams in granitic and sedimentary bed material.

wood, vegetation, and distribution of grain sizes has a larger impact on sediment size than the sediment supply. These hydraulic roughness elements cause a fining of the bed material. The gradient is related to the transport capacity. The ANCOVA model indicates that, as the transport capacity increases, the percent of fine sediment decreases (Montgomery and Buffington, 1997).

5.3. Vegetation controls and channel response

Vegetation has a significant influence on the percent of fine sediment, D_{84mod}, BWmod, Poolmod, unstable banks, and wood in the channel. Vegetation understory cover is related to most of the channel morphologic variables. The percent fine sediment and the D_{84mod} change significantly with the PCA axis that represents the understory vegetation from bankfull to one channel width away from the stream. This indicates a localized control on sediment input from the surrounding area. As the understory vegetation increases, the amount of fine sediment decreases. The first PCA axis represents a greater amount of willow, spruce, and alder as the value increases along that axis. The second axis represents an increase in spruce, alder, and common gooseberry (*Ribes inerme*) and a decrease in willow cover. Both axes correspond to an increasing density of vegetation with an increase in the PCA score. Project streams with a low gradient, low density of understory vegetation, and high wood load have a larger percent of fine sediment than the reference streams.

Unstable banks are significantly related to vegetation type and density along the stream bank. An increase with the PCA1SE variable is related to a decrease in unstable banks. Also, an increase in the PCA1USE is related to a decrease in the BWmod variable. An increase along these PCA axis scores is related to an increase in willow understory along the stream edge. Moss and graminoids also increase along this axis. Previous studies have shown that grass can increase bank stability and can correspond to narrower channels (Murgatroyd and Ternan, 1983). The percent of unstable banks decreases with higher scores along this axis. Therefore, an increase in willow and graminoids is significantly related to increasing bank stability and decreasing w_b.

Vegetation below w_b increases bank stability via several mechanisms. Root reinforcement from vegetation increases the cohesiveness of the bank material (Abernethy and Rutherfurd, 2000; Pollen and Simon, 2005). Rooting density and depth are important in increasing the factor of safety, so that a greater amount of shear has to be applied to cause bank failure (Huang and Nanson, 1998; Abernethy and Rutherfurd, 2000; Pollen and Simon, 2005). An increase in the amount of vegetation can also reduce the soil moisture content, reducing the pore water pressure and therefore increasing the factor of safety for the banks (Thorne, 1990; Gurnell et al., 2002). Vegetation reduces the soil moisture content by intercepting rainfall and by transpiration from the soil (Simon et al., 2004). Both root reinforcement and decreased soil moisture content are important for stabilizing banks (Abernethy and Rutherfurd, 2000). Increased bank stabilization is particularly important for the undercut banks found in the stream channels in this study.

Riparian vegetation can also significantly increase the roughness of the boundary, increasing the height of the zero velocity plane, and reducing the shear along the banks (Thorne, 1990). This process then reduces erosion of the banks and therefore increases bank stability. Fig. 6 shows two reference streams with different vegetative characteristics. Lenawee is a stream dominated by willow cover above and below w_b. Jones Gulch R3 has a much higher spruce and fir overstory with willow, bush honeysuckle, and common gooseberry in the understory. The willow in the understory of Lenawee Creek has branches that actually reach into the flow, although the plant is not rooted in the channel. The slow process of bank failure can be observed in the picture of Jones Gulch. The banks are deeply undercut and one tree has already fallen. The next tree is leaning towards the stream, indicating that at some point the bank will fail and that tree will fall. The added weight of a tree on an undercut bank will eventually cause subsidence and failure (Rutherfurd and Grove, 2004).

The stability of banks is related to vegetative cover as well as bank height (Abernethy and Rutherfurd, 2000; Anderson et al., 2004). Once a stream reaches a critical bank height, the reinforcement by roots decreases because roots extend a limited depth into the soil profile (Abernethy and Rutherfurd, 2000; Pollen and Simon, 2005), but the factor of safety is higher for banks with vegetation versus unvegetated banks (Pollen and Simon, 2005).

The ANCOVA model shows that vegetation type and density are significantly related to bank stability, but the influence of this variable is not as large as the influence of graded density after adjusting for vegetation type. Therefore, the degree of unstable banks along a reach is mitigated by vegetation, but notably increases with an increase in graded density. The other morphologic variables are likewise influenced by vegetation cover, but still alter with ski slope development.

5.4. Development and channel response

The development variables graded density, drainage density, yield increase, and cleared area within 90 m of the stream were found to have the largest impact on the stream channel variables. Table 3 shows a compilation of each of the ANCOVA models and the change in each response variable in comparison to the significant development variable. The full ANCOVA results are presented in David (2007). A significant difference is found between project and reference streams for all channel morphologic variables except for wood found in the channel.

We expected that an increase in flow from snowmaking and tree-clearing would cause bed coarsening (Montgomery and Buffington,

Fig. 6. Comparison of understory vegetation type and density on two reference stream channels.

1998; MacDonald and Stednick, 2003). An increase in stream flow should increase stream power and therefore bedload transport rates (Jones and Grant, 1996). The bed material in a stream is a function of rates of bedload transport and sediment supply (Buffington and Montgomery, 1999a). Bedload transport is, in turn, related to excess shear stress available for sediment transport (Buffington and Montgomery, 1999a,b). Step-pool and cascade reaches of these channels are usually supply-limited, therefore the finer bed material is moved out of the system (Montgomery and Buffington, 1998).

The ANCOVA models for the D_{84mod} and for the percent fine sediment (Table 3) show that project streams have significantly finer sediment in the channel versus the reference streams. The fact that the project streams have significantly finer sediment than the reference streams suggest that increased sediment load from roads overcomes the transport capacity in these streams (Jones and Grant, 1996; Luce and Black, 1999). Fig. 7 shows sediment eroded from a road in Breckenridge, CO. This sediment is a potential sediment source area for Lehman Gulch with a potential delivery route via the waterbars. Observations of roads, water bars, and graded slopes confirm that there is a significant amount of mass wasting of fine sediment toward the stream channel.

The results of the ANCOVA models show that there is more than one mechanism responsible for an increase in fine bed sediments (Table 3). Wood load is significantly related to an increase in fine sediment and a decrease in the D_{84mod}. The influence of wood on percent of fine sediment is discussed in Section 5.2.

Other development variables found to be significantly related to sediment size in the streams were percent increase in drainage density and graded density. The drainage density is representative of drainage ditches from roads connected to the stream. Graded areas on the ski slopes are places where the top soil has been removed. Revegetation of these graded slopes is difficult and, therefore, runoff and erosion increase off these slopes (Ruth-Balaganskaya and Myllynen-Malinen, 2000; Wipf et al., 2005). Graded areas are connected to the streams via waterbars. The USDA Forest Service found that these areas have to be mapped in the field for appropriate values of connected waterbars and increase in drainage density to be included (M. Weinhold, Forest Hydrologist, White River National Forest, personal communication, 2008).

The percent increase in drainage density is significantly related to an increase in the D_{84mod}, which indicates that the bed is coarsening from inputs from the connected roads. Data showing the further increases in drainage density from connected waterbars were not available for analysis. The ski slopes are areas that have been cleared of trees and have an increase in water from a decrease in evapotranspiration and from snowmaking (Wright Water Engineers and Leaf, 1986). The increased water is then routed to the stream more efficiently through the water bars and ditches next to roads. The flow routing through water bars may cause an increase in the magnitude and timing of the peak, which increases the transport capacity in the channel and hence the D_{84mod} (Montgomery and Buffington, 1997). The magnitude of change in the D_{84mod} with an increase in drainage density is very small in relation to the other significant variables in the ANCOVA model (Table 3): bedrock geology, wood, project/reference stream.

Graded density encompasses all the graded areas in a basin, whether or not they are connected to the stream directly. The graded density is significantly related to the percent of unstable banks and percent of undercut banks. This relationship indicates that the influence of the graded density on the stream is an increase in flow. The removal of the topsoil on graded slopes causes a decrease in infiltration, therefore changing the flow paths and allowing runoff to reach the stream along a faster route. The increase in flow increases the transport capacity, which can cause bank erosion without a corresponding increase in sediment supply (Buffington and Montgomery, 1999a). The graded areas are not necessarily connected directly to the streams, and therefore an increase in graded area does not necessarily correspond to an increase in sediment supply. The localized control of increased bank erosion leads to bed fining, which balances the bed coarsening from the increase in the magnitude of the peak flow from the percent increase in drainage density (Davis and Gregory, 1994).

6. Conclusions

Our research focused on steep gradient cascade and step-pool channels that are generally considered to be less responsive to changes in water and sediment yield than lower gradient pool-riffle channels (Ryan and Grant, 1991; Montgomery and Buffington, 1997). Nonetheless, we found significant differences in channel morphology between basins that have ski slope development and otherwise analogous streams that drain catchments without development. These differences are mitigated by many factors, such as vegetation, timing of development, extent of development, and underlying lithology. Despite the complex nature of these systems, some project streams differ significantly from the reference streams. These differences appear as a combination of changes in the morphology, such as increase in undercut banks, unstable banks, and fine sediment. The project streams in granitic material and low vegetative cover in the understory appear to be most altered. The CART analysis, ANOSIM, and ANCOVA models show that these project streams are outside the range of variability from the reference streams. The observed changes in morphology in these project streams are beyond the changes expected in these systems without any development in the basin.

Fig. 7. Sediment shed from a road in Breckenridge toward Lehman Gulch.

The CART analysis, the ANCOVA models, and the ANOSIM all indicate that vegetation and geology exert a major influence on channel morphology. These various statistical techniques also identified significant differences in channel morphology with increased development in the basin. The measures of development most strongly associated with changes in the stream are cleared areas within 90 m of the stream, graded density, and drainage density.

Each hypothesis developed for this project tests response variables that are of concern to the USFS and other resource-management agencies for understanding the controls on channel morphology in steep headwater streams and how these controls change with ski slope development. Significant differences were found between all the response variables in project and reference streams except for the amount of wood in a stream. The amount of wood is more significantly related to wood recruitment from the surrounding vegetation.

Vegetation is a mitigating factor in changes of all the response variables. Bank stability increases with increased willow and graminoids below bankfull stage. Pool depth and percent of fine sediment decrease with an increase in willow understory above bankfull. The increase in willow understory results in a decrease in unstable banks and erosion off the surrounding area. Therefore, percent of fine sediment decreases in streams with a large amount of willow in the understory.

The CART analysis did reveal thresholds in the response variables. The project streams determined to be the most impacted had a combination of >29% undercut banks, >16% unstable banks, and >35% fine sediment. These thresholds can be used to determine the degree of impact on a stream and whether it has degraded from reference conditions. Although these thresholds are useful guides, response variables are missing in the analysis that needs to be considered when looking at degradation in a stream. One variable that should be included in any further analysis of stream channels is degree of incision.

Stream channel adjustment to ski slope development is significantly related to an increase in drainage density and graded density. Percent increases in yield from snowmaking and tree-clearing are also significant, but to a lesser extent. The CART analysis revealed that the project streams that are most impacted are those that are in granitic bed material, at a higher gradient, and with a greater amount of overstory cover. The CART also showed that stream channel morphology mainly reflects *A*, *S*, vegetation, and underlying geology. The impact of development has a smaller effect on stream morphology than these four variables. The controls on channel morphology changed for reference versus project basins. *A* and *S* controlled the channel morphology in streams with no development, whereas vegetation became more significant in the developed basins.

The results presented here provide an initial quantification of the effects of ski slope development on steep, headwater streams in the semiarid Rocky Mountains of Colorado and suggest that development should be most restricted in catchments underlain by granitic geology and where stream corridors lack extensive stands of willows. Subsequent research that applies the techniques discussed here to lower gradient streams and to other environments with ski slope development should prove useful in helping managers of natural resources to develop similar guidelines that identify stream catchments most likely to show changes in channel morphology as a result of ski slope development.

Acknowledgements

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