1373

Morphology and Processes of Valley Floors in Mountain Streams, Western Cascades, Oregon

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Development of valley floor landforms and channel morphology in headwater streams is strongly influenced by processes external to the channel. The distribution of landforms on valley floors of two fifth-order mountain streams in western Oregon exhibit distinctive reach-to-reach variations, as defined by a valley floor width index: the ratio of approximate width of Holocene valley floor (surfaces less than or equal to 3 m in height) to active channel width. This variation corresponds to the distribution of bedrock outcrops and hillslope landforms, including large landslides and alluvial fans, which constrain the channel. Lowest valley floor width index values (less than or equal to 1.3) occur where the channel is incised in bedrock or where landslides or alluvial fans encroach upon the valley floor, commonly forcing the channel against bedrock in the opposite valley wall. Highest valley floor width index values (greater than or equal to 4.0) occur upstream of these constrained reaches where valley floors aggrade and little bedrock is exposed. Widths of valley floor landforms of different origins do not increase uniformly with increasing valley floor width; active channel widths remain relatively constant while reaches with greater valley floor width generally exhibit greater widths of floodplains created by fluvial processes and/or debris flows. Hillslope and tributary processes also influence the channel gradient and determine the size and density of boulders in the channel. Highest boulder densities and steepest channels occur where channels are bordered by alluvial fans, terraces containing debris-flow deposits, and active or inactive large landslides. Reaches differ in their susceptibilities to reworking by fluvial and non-fluvial processes. The distribution of landforms of fluvial origin varies in relation to reach-averaged shear stresses generated during large floods. The pattern of landforms of debris-flow origin is determined by the valley floor geometry, location of debris-flow producing tributaries, and the longitudinal sequence of reaches. Changes in valley floor morphology in mountain streams occur rapidly and episodically during infrequent, intense floods, in contrast to the more gradual, fluvial reworking of valley floor sediment in low-gradient alluvial streams.

1. INTRODUCTION

The morphology and dynamics of valley floor environments in mountain landscapes differ markedly from their lowland counterparts but have received comparatively little attention. In contrast to wide, low-gradient streams, where valley floor morphology reflects the predominance of fluvial processes, morphology of narrow, high-gradient streams is dominated by the interplay of fluvial processes with processes and landforms external to the channel. The latter include landslides, debris flows, alluvial fans, and bedrock outcrops. Interpreting the geomorphic, sedimentologic, and ecologic patterns of valley floor environments requires appreciation for how hillslope processes and landforms influence channel and valley floor morphology.

Despite the importance of hillslope processes as modifiers of valley floor morphology in mountain landscapes, there has been little attempt to examine this subject systematically, although aspects of this problem have been explored. Landslides, debris flows, and alluvial fans were recognized as important agents modifying valley bottoms by *Hack and Goodlett* [1960] in their landmark paper on

Natural and Anthropogenic Influences in Fluvial Geomorphology
Geophysical Monograph 89

geomorphology of Appalachian watersheds. More recent work has emphasized the role of bedrock controlling channel and valley floor morphology [*Baker,* 1984; *Lisle,* 1986; *O'Connor et al.,* 1986; *Baker and Pickup,* 1987; *Ashley et al.,* 1988; *Baker and Kochel,* 1988; *Kelsey,* 1988; *Jacobson et al.,* 1989; *Grant et al.,* 1990; *Miller,* 1990a] and debris fans as prominent landforms affecting channel planform and gradient [*Kieffer,* 1985; *Miller,* 1990b]. Many workers have documented the importance of mass movements leaving persistent impacts on mountain valleys during exceptional floods [e.g., *Tricart,* 1962; *Stewart and LaMarche,* 1967; *Scott and Gravlee,* 1968; *Nolan and Marron,* 1985; *Kochel,* 1988; *Jacobson et al.,* 1989; *Miller,* 1990a, b), and there has been some effort to describe the sedimentologic and rheologic characteristics of debris flow and debris flood deposits on valley floors [*Costa and Jarrett,* 1981; *Jarrett and Costa,* 1986; *Costa,* 1988; *Carling,* 1989].

The purpose of this investigation is to examine how variation in valley floor morphology in mountain landscapes corresponds to hillslope processes' and to contrast the dynamics of valley floors in mountain and lowland streams. Drawing from field studies of 5-km lengths of fifth-order valley floor in two streams typical of the western Cascade Range of Oregon, we examine the pattern and areal extent of valley floor landforms in relation to bedrock outcrops and hillslope processes. We hypothesize that hillslope processes control the distribution of valley floor landforms by determining the type, extent, and energetics of geomorphic processes operating on the valley floor. Our interpretations of geomorphic dynamics of montane valley floors are contrasted with the type and rate of change observed in lower-gradient, meandering river systems.

Hierarchical classifications of stream networks and watersheds are increasingly being utilized in riverine research and management [*Rosgen,* 1985, 1994; *Frissell et al.,* 1986; *Kishi et al.,* 1987; *Grant et al.,* 1990; *Montgomery and Buffington,* 1993] and have been employed to classify streams ecologically [*Kani,* 1944, 1981; *Mizuno and Kawanabe,* 1981; *Gregory et al.,* 1991; *Hawkins et al.,* 1993). By this view, drainage basins are composed of lengths of stream and associated valley floor environments at several spatial scales that are more or less homogenous with respect to controlling variables of geology, substrate, hydraulics, and hillslope influences (Figure 1). This approach is useful for expressing scales and sources of variation in watershed morphology that are not well captured in the classic continuum view of stream and valley morphology as controlled primarily by discharge [*Leopold and Maddock,* 1953; *Leopold et al.,* 1964; *Vannote et al.,* 1980; *Bhowmik,* 1984].

Within this hierarchical scheme, the channel unit scale (e.g., pools, riffles; see Figure 1) has been extensively studied for decades in both low- and high-gradient streams [e.g., *Richards,* 1976; *Keller and Melhorn,* 1978; *Grant et al.,* 1990; *Takahashi,* 1990]. The reach scale, the subject of this paper, has received much less attention, in part because interpreting reach morphology requires considering both fluvial and extra-fluvial influences. We develop this concept by examining how the morphology and distribution of valley floor landforms reflect hillslope processes. Understanding the distribution and dynamics of reaches is important for interpreting drainage basin structure and long-term behavior, predicting channel and valley floor conditions in unsampled watersheds, and designing effective stream and riparian management strategies.

We distinguish reaches as segments of valley floor separated by distinct breaks in valley floor width' and examine the correspondence between reaches and the type and degree of constraint on the width of the valley floor imposed by hillslope processes. Major agents of constraint in this study included bedrock outcrops, large landslides, and large alluvial fans. Bedrock outcrops are passive constraining agents. Active, slow-moving landslides and accreting alluvial fans, the latter growing by periodic accumulation of debris flow and bedload deposits delivered from tributary streams, may actively constrict valley floors and channels. In this study, reaches typically ranged from several hundred meters to several kilometers in length.

2. STUDY SITES

At the lower ends of the study sites, Lookout Creek and French Pete Creek drain 67 and 83 km^2, respectively, of moderate to steeply sloping land in the western Cascade Range of Oregon (Table 1, Figure 2). Elevations of the two basins range from 410 to more than 1600 m. Bedrock is a mixture of Tertiary volcaniclastic rocks and lava flows cut by scattered dikes [*Peck et al.,* 1964; *Swanson and James,* 1975a; *Priest et al.,* 1983; *Sherrod and Smith,* 1989]. Landforms have been sculpted by fluvial, glacial, and mass movement processes. The latter include shallow, rapid movements of soil on hillslopes (debris slides); rapid movements of alluvium, colluvium, and organic matter down stream channels (debris flows); and large, slow-moving landslides (earthflows) [*Swanson and James,* 1975a, b]. Streamflow regimes are characterized by high winter flows from November through April, with peak flows occurring primarily during rain-on-snow events [*Harr,* 1981]. The largest recorded peak flow for Lookout Creek was 185 m^3/s in December 1964, a storm that

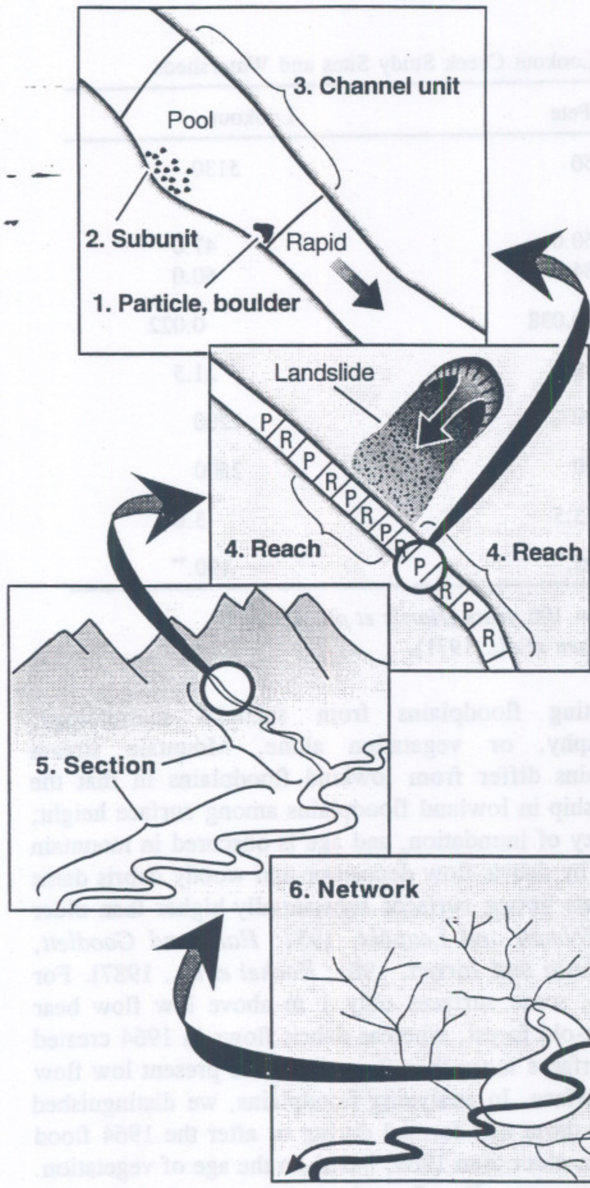

Fig. 1. A hierarchical model for organizing stream systems and associated landforms.

produced extensive debris slides and flows in tributaries. French Pete is ungaged but also experienced high flows and mass movements during this storm. This storm, which was regional in extent, left prominent landforms along the valley bottoms of both streams (described below) as well as many other watersheds throughout the Pacific Northwest [*Waananen et al.,* 1971]. A prolonged summer drought from July through September results in a very constant low flow discharge of approximately 0.015 $m^3/s\ km^2$ for both watersheds.

3. IDENTIFICATION OF VALLEY FLOOR LANDFORMS

The distribution of landforms in the valley floors of these two basins was examined by detailed mapping. The mapping was done with tape, compass, and clinometer using a baseline established along the channel and transects spaced at 100-m intervals extending from the channel to the base of the valley wall. We mapped geomorphic landforms as small as 10 m^2 and with as little as 0.5 m difference in elevation from adjacent landforms. Landforms were described by type (defined below) and height above low water level, which remained essentially constant throughout the month-long mapping period. Dense forest cover and the very coarse substrate of cobbles and boulders precluded stratigraphic analysis. Interpretation of age and origin of landforms was based on surficial morphology, age of vegetation, and other features such as orientation and degree of decay of woody debris accumulations, many of which dated from the 1964 flood.

The valley floors are composed of (1) the active channel, (2) secondary channels, (3) a progression of floodplains and terraces generally increasing in height away from the channel, and (4) alluvial fans (Figures 3, 4). These are described in the same order below.

The active channel is the area still inundated at summer low flow plus the adjacent unvegetated channel shelf [in the sense of *Hupp,* 1982; *Osterkamp and Hupp,* 1984] and gravel bars, plus secondary channels fed perennially from the main channel. These landforms are typically less than 0.5 m above low flow and are inundated by flood flows several times each year. Transport of coarse bedload and woody debris over these surfaces repeatedly prunes vegetation (mainly willow and red alder) and maintains a shrubby growth form on exposed bars.

Intermittent, ephemeral, and abandoned channels comprise a separate landform: the secondary channels. These channels typically are incised into terrace or floodplain landforms, and some have abundant woody debris and perennial vegetation within the channel. Some may originally have formed as primary channels but now carry discharge from a tributary or spring.

Floodplains are vegetated landforms less than or equal to 3 m above the low flow water surface and sloping in the down-valley direction parallel with the main channel. They include both coarse-textured fluvial deposits and boulder-berms resulting from debris-flow runout or fluvial deposition due to abrupt expansion of the valley floor [*Carling,* 1989]. In these two streams, the 3-m cutoff represents the approximate maximum height of Holocene-age deposits, based on field evidence and paleohydraulic

TABLE 1. Geomorphic Characteristics of the French Pete and Lookout Creek Study Sites and Watersheds

	French Pete	Lookout
Length of study site (m)	4950	5130
Drainage area (km^2)		
Upstream end	60.0	47.0
Downstream	84.0	60.0
Mean channel slope (m/m)	0.038	0.022
Mean active channel width (m)	18.1	21.5
Mean basin elevation (m)	1300	1200
Mean annual precipitation (mm)	2500	2500
Mean annual discharge (m^3/s)	3.5	3.6
Peak discharge (m^3/s)	95.*	190.**

*From regional flood frequency analysis; estimated recurrence interval = 100 years [*Harris et al.*, 1979].
**From gage record; estimated recurrence interval = 100 years [*Waananen et al.*, 1971].

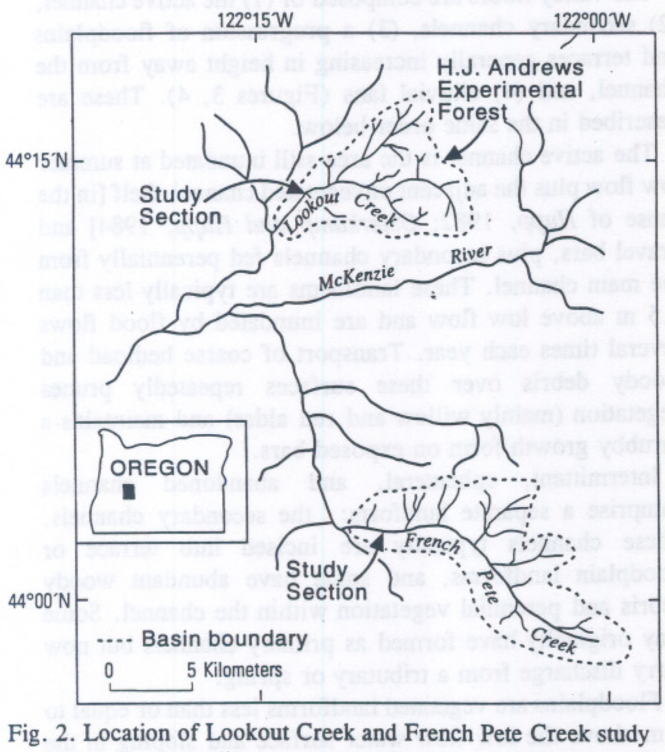

Fig. 2. Location of Lookout Creek and French Pete Creek study sections. Vertical lines on streams show upstream and downstream boundaries.

reconstruction [*Swanson and James*, 1975b; *Grant et al.*, 1990]. We defined floodplains using this criterion to reflect the extent of valley floor that potentially has been reworked during the Holocene and because of the difficulty in interpreting floodplains from surficial morphology, stratigraphy, or vegetation alone. Mountain stream floodplains differ from lowland floodplains in that the relationship in lowland floodplains among surface height, frequency of inundation, and age is obscured in mountain streams by debris-flow deposition and woody debris dams that create young surfaces substantially higher than older ones [*Wolman and Leopold*, 1957; *Hack and Goodlett*, 1960; *Costa and Jarrett*, 1981; *Kochel et al.*, 1987]. For example, some surfaces only 1 m above low flow bear 500-year-old forest, whereas debris flows in 1964 created fresh surfaces more than 2 m above the present low flow water surface. In analyzing floodplains, we distinguished between those that formed during or after the 1964 flood and those older than 1964, based on the age of vegetation.

Terraces are valley floor features greater than 3 m but less than 10 m above the low flow water surface. Terraces underlain entirely by alluvium, strath terraces cut in bedrock, and alluvial deposits overlapping bedrock are all found in the study area. High terrace remnants greater than 10 m above the low flow channel are also present but rare and are considered valley wall features (Table 2). Ages of terraces are poorly known, but all predate the 500-year-old forest growing on them. Most terraces have surficial deposits of Mazama ash (6600 yrs B.P.) and are therefore probably late Pleistocene in age [*Swanson and James*, 1975a; *Gottesfeld et al.*, 1981].

Alluvial fans, 140 to 66,000 m^2 in size, have developed at the junctions of tributary streams and the mainstem

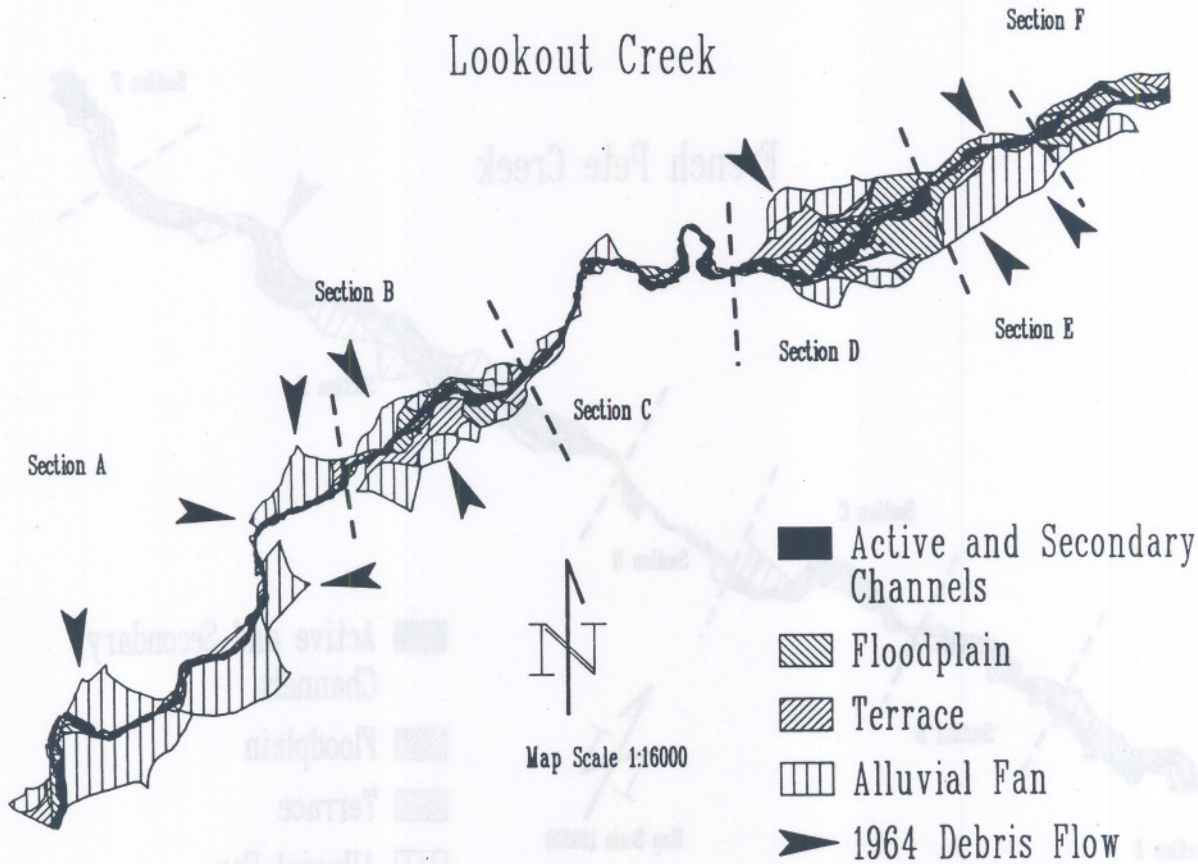

Fig. 3. Maps of the two study sections showing reach boundaries and locations of channels, floodplains, terraces, and alluvial fans as defined in text. Debris flows that occurred in the December 1964 storm also are shown. Bedrock outcrops occur where the stream flows against the valley wall. (a) Lookout Creek. (b) French Pete Creek.

where the valley floor is or was wide enough to accommodate fan deposits supplied by tributaries. Both active and inactive fans are present (Figure 4). Tributary streams on active fans generally are incised less than 4 m below the fan surface, and channels flowing over the fan may have the form of discontinuous gullies. Bedload and debris flows from tributary basins can be deposited on the fan front or margins, adding to fan volume. Inactive fans are those deeply incised by the tributary stream and cut at the toe by the mainstem, leaving fan remnants 5 m or more above the present channels. These fan fragments are inactive in the sense that they no longer accumulate material transported as bedload or debris flow from tributaries; so sediment and debris flows pass directly to the mainstem channel. Some fan fragments in the study areas have been inactive since at least the time of deposition of Mazama ash and possibly much longer [*Swanson and James,* 1975a].

4. SPATIAL PATTERN OF VALLEY FLOOR LANDFORMS

4.1 *Reach Delineation*

To analyze the effects of external controls on valley floor geometry, we first delineated reaches based on the width of the valley floor. Two questions motivated this analysis. First, how do different external controls influence the width of the valley floor, and second, how does the distribution of landforms of different types change in relation to those controls? The width of the valley floor was measured on the maps at 50-m intervals along and perpendicular to the stream. We expressed the width of the valley at each station using a *valley floor width index* (VFWI), defined as VFWI = $(W_{ac} + W_{fp})/W_{ac^*}$, where W_{ac} and W_{fp} are the widths of the active channel and floodplain

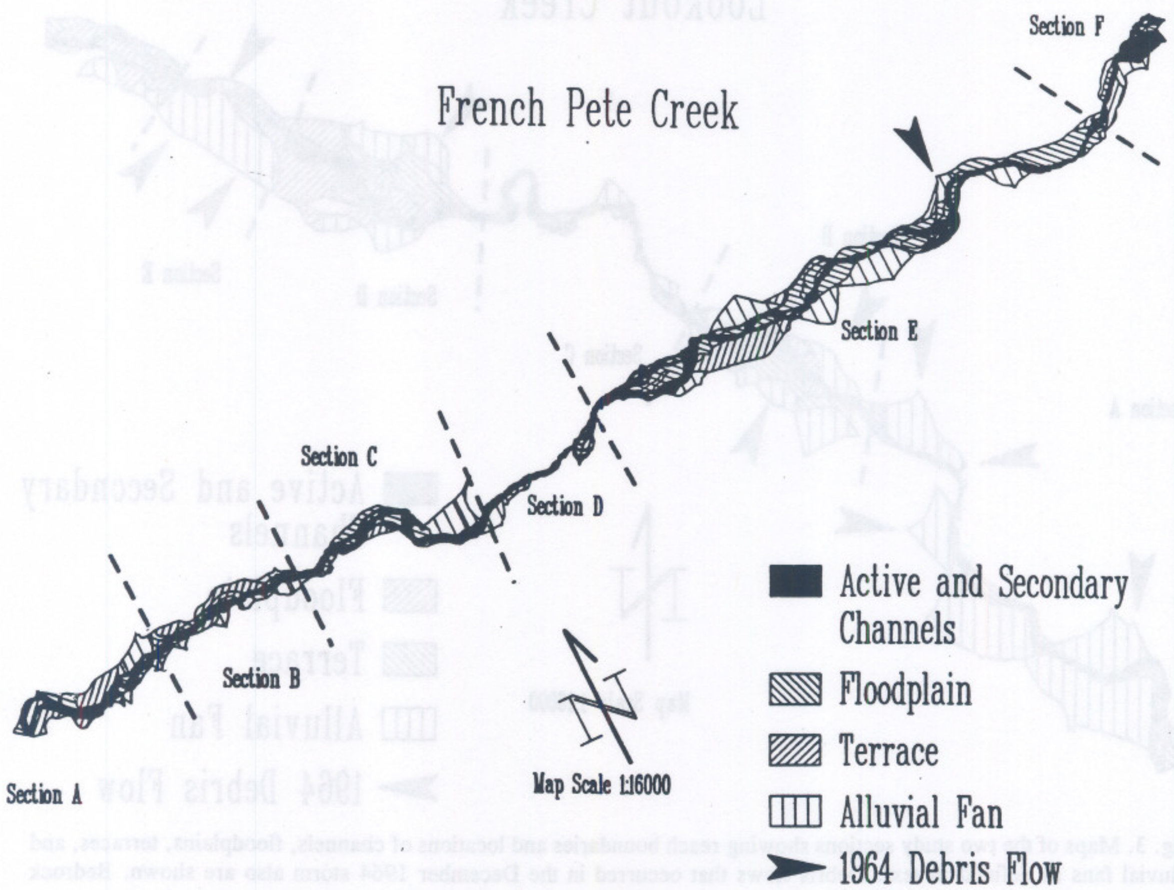

Figure 3 (continued)

landforms, respectively, and W_{ac*} is the average width of the active channel for all reaches at each site (Figure 4). The VFWI therefore provides a measure, in channel widths, of the variation between narrow and wide valley floors. Only the active channel and floodplain widths were considered in defining the VFWI in order to emphasize that portion of the valley floor that has been most active during Holocene time. The VFWI is potentially useful as a dimensionless index in comparing the geomorphic behavior of a wide range of reaches and streams. Its inverse, for example, has been used to discriminate between reaches experiencing scour or deposition during floods [*Wolman and Eiler*, 1958].

The valley floor width index was calculated as a 200-m running average for each site. We defined reaches as lengths of valley floor at least 300-m long bounded by changes of 25% or more in the smoothed valley floor width index (Figure 5a, b). On this basis, we delineated six reaches in French Pete and five in Lookout Creek. An additional reach (LE) was delineated in Lookout Creek where a large alluvial fan complex constricts the channel, even though the length criterion was not strictly met in this case (Figure 3a, b; Tables 2, 3). Reach identification is explained in the caption to Figure 6.

4.2 *Controls on Valley Floor Width*

Variation in reach widths results from terraces, alluvial fans, and valley wall landforms, including earthflows, bedrock outcrops, high terraces, and colluvium (Table 2; Figure 3a, b). Some reaches are dominated by a single type of constraint, i.e., valley walls (reach FC) or terraces (reach LD). Most reaches have at least two factors controlling valley floor width, such as valley walls and fans (reaches FD, FE, LE), terraces and fans (reaches FB, LA, LB), or terraces and valley walls (reaches FA, FF, LC, LF). Bedrock outcrops along the valley wall are important constraints in reaches FA, FD, FE, FF, LA, LC, and bedrock also underlies the strath terraces constraining the valley floor in reaches LA and LB. Earthflow complexes

TABLE 2. Reach Characteristics and Constraining Agents in French Pete and Lookout Creek Study Sites.

Reach*	Length (m)	Agents of Constraint**	Sinuosity (m/m)	Channel Gradient (%)	Valley Floor Width Index (m/m)	Channel Perimeter in Bedrock (%)	Average boulder density (No./100 m)	Perimeter of Valley Floor ≤3-m High Bounded By: Fans (%)	Terraces (%)	Valley Wall (%)	Active-active (%)	Active-passive (%)	Passive-passive (%)
FRENCH PETE CREEK													
FA	900.0	Terraces, valley wall (bedrock)	1.2	4.2	2.2	5.9	22.4	19	60	21		19	81
FB	400.0	Fans, terraces	1.0	5.5	1.3	2.2	34.7	47	38	15		47	53
FC	600.0	Valley wall (high terrace)	0.9	3.9	2.9	6.0	13.7	18	14	68		18	82
FD	700.0	Valley wall (earthflow, bedrock), fans	1.2	3.3	1.3	9.5	18.4	27	10	63		90	10
FE	2000.0	Valley wall (high terrace), fans	1.1	3.5	4.0	10.1	13.0	25	21	53		25	75
FF	350.0	Terraces, valley wall (bedrock)	1.3	3.3	1.8	16.0	2.7	3	62	35		3	97
TOTAL/ SITE AVERAGE	4950.0		1.1	3.8	2.8	8.8	16.6					32.5	67.5
LOOKOUT CREEK													
LA	1800.0	Fans, strath (bedrock) terraces	1.1	1.9	1.2	44.1	5.4	43	40	17		80	20
LB	690.0	Terraces, fans	1.0	2.1	2.8	13.1	6.9	29	51	20	33	67	
LC	1130.0	Valley wall (earthflow, bedrock)	1.2	2.8	1.3	23.6	12.2	11	31	58		75	25
LD	690.0	Terrace, valley wall (colluvium)	1.3	2.2	6.9	0.5	1.1	16	71	13		16	84
LE	375.0	Fans, valley wall (colluvium)	1.0	2.2	2.8	1.6	6.5	39	28	33	25	75	
LF	445.0	Terrace, valley wall (colluvium), fans	1.0	2.0	5.5	4.9	0.1	26	44	30		25	75
TOTAL/ SITE AVERAGE	5130.0		1.1	2.2	2.6	23.3	6.2				6.5	65.7	31.4

*Reaches are listed in order from downstream to upstream.

**Terrace and valley wall constraining agents are further modified by the dominant underlying material or process.

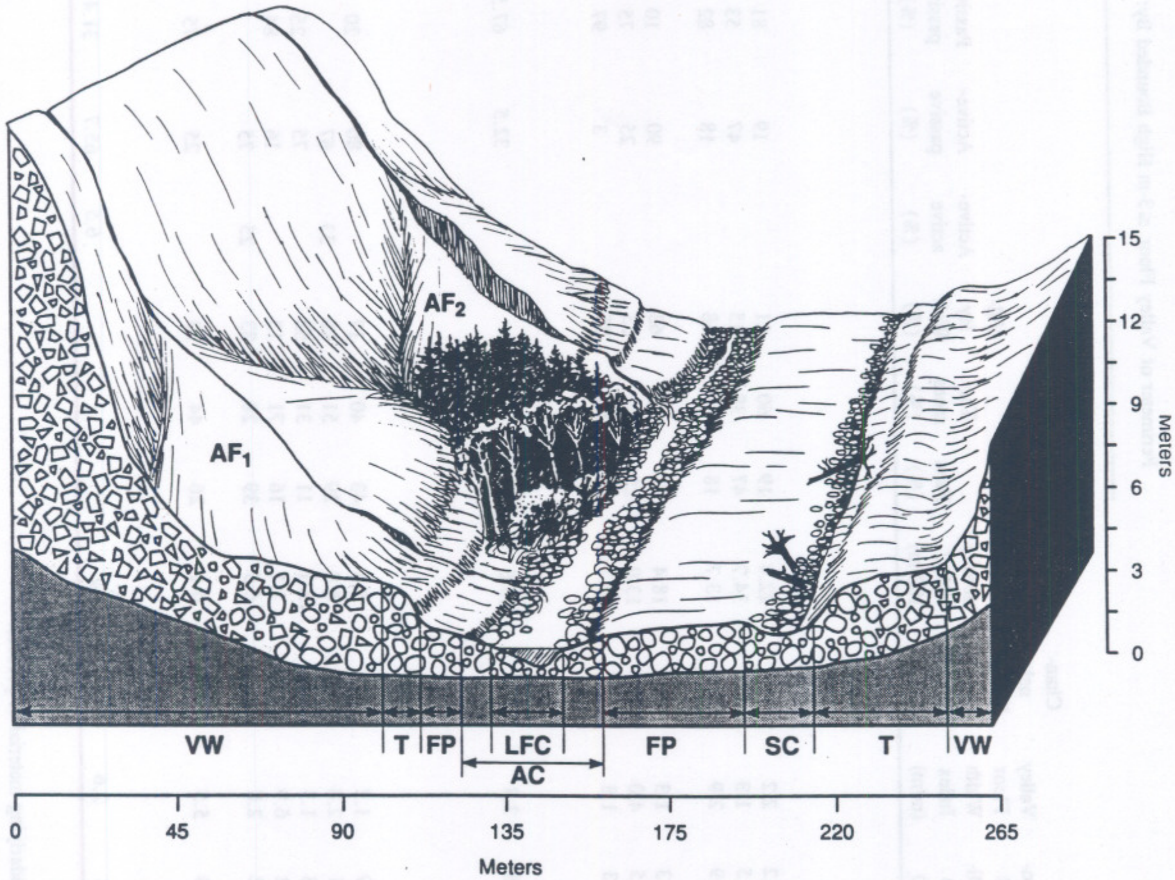

Fig. 4. Schematic diagram of valley floor surface types. Abbreviations used: LFC = low-flow channel; AC = active channel; FP = floodplain; SC = secondary channel; T = terrace; AF$_1$ = unincised, active alluvial fan; AF$_2$ = incised, inactive fan; VF = valley wall.

encroach on the valley floor in reaches FD and LC. Narrowest valley floors occur where fans (FB, LA) or earthflows (FD, LC) encroach upon the valley floor, forcing the channel against bedrock in the opposite valley wall. Widest valley floors (FE, LD) occur immediately upstream of the most actively constricting earthflow reaches. Little bedrock is exposed in the wide reaches; in general, there is a negative relation between valley floor width and percent of channel margin length comprised of exposed bedrock. This is presumably due to burial of bedrock in wide, alluviated reaches (Table 2).

In general, there are three classes of valley floor-valley margin interaction: active-active, where the valley floor is bounded by two active constraining processes (i.e., earthflows, active alluvial fans) on either side of the channel; active-passive, where an active constraining process pushes the stream against a passive constraint (i.e., terraces, bedrock, inactive fans, colluvium); and passive-passive, where no active constraint is occurring. The active-active type is quite rare and found in only two reaches (LB and LE) comprising 6% of channel length in Lookout Creek. Most of French Pete Creek falls in the passive-passive category (68%), while most of Lookout Creek is in the active-passive category (66%) (Table 2), implying that channel-adjacent hillslope processes may currently be more active in Lookout Creek than in French Pete Creek.

4.3 *Distribution of Landforms by Reach*

The proportions of valley floor occupied by different landforms varies by reach. We consider the 12 sampled reaches as a population along a continuum of valley floor width and examine how landforms of different types contribute to increasing valley floor width (Figure 6, Table 3).

Active and secondary channels. The width of the active channel is relatively constant up to a valley floor width

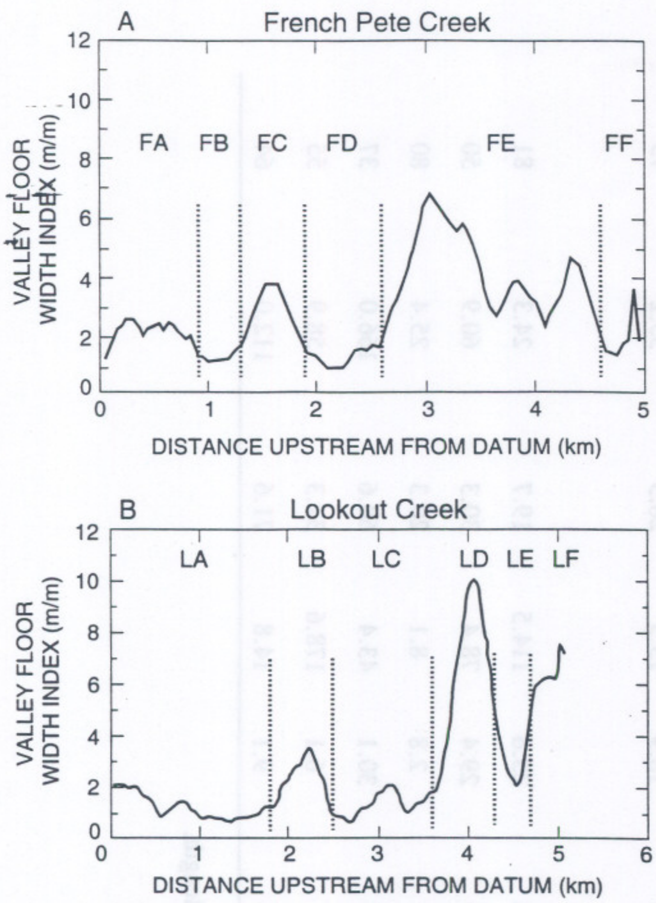

Fig. 5. Plot of valley floor width index (VFWI) as a function of distance upstream for the two study sites. VFWI was calculated as a 200-m running average of the ratio of active and floodplain widths to the average active channel width for the entire site, based on measurements of valley width taken at 50-m intervals. (a) Lookout Creek. (b) French Pete Creek.

index of 4.0, above which it increases (Figure 6). Reach-to-reach variation overwhelms any systematic downstream increase in channel width. Indeed, upstream reaches (FE, LF, LD) have the widest channels at each site. Secondary channels are most extensive in reaches with wide valley floors (VFWI > 1.8) (Figure 6). Reaches with relatively narrow valley floors (VFWI < 2.0) average only about 1600 m^2/km of secondary channel, whereas reaches with wider valley floors (VFWI ≥ 2.9) average 8100 m^2/km.

Floodplains 1964 and younger. These include floodplains that bear vegetation originating from fluvial disturbance in 1964 or more recently. Wide valleys tend to have wide, young floodplains, although the proportion of valley floor in this landform does not increase linearly with valley floor width. Instead, there is a marked increase at a valley floor width index of approximately 2.8; widths of post-1964 floodplains average 4.3 m below this value (n = 6) and 14.0 m above it (n = 6). The most extensive development of this landform occurs in reaches where fluvial disturbances and large debris flows from tributary streams occurred during the 1964-1965 winter (reaches LD, LE, LF, and FE) (Figure 3a, b).

Pre-1964 floodplains. Pre-1964 floodplains have vegetation older than 30 years old growing on them. Reaches vary widely in the width of this landform, from less than 1 m (FD) to over 100 m (LD). Unlike other surfaces, widths of pre-1964 floodplains increase linearly with valley floor width index (r^2 = 0.87). Little of this surface type occurs in reaches with valley floor width index less than 1.8, which include reaches constrained by earthflows (FD and LC), bedrock (LA), and terraces (FB). These reaches also have the lowest proportion of valley floor width disturbed by the 1964 flood. Development of pre-1964 floodplain surfaces is limited in reaches with low valley floor width index by two related factors which lead to either erosion of deposited material or nondeposition: limited space for deposition and very high shear stresses during flood events through the narrow canyons [*Nanson*, 1986; *Baker and Pickup*, 1987; *Kelsey*, 1988; *Miller*, 1990a, b].

The reaches showing most extensive development of pre-1964 floodplain surfaces are also those with the widest 1964 floodplains (Figure 6). A debris-flow origin for some pre-1964 floodplains is inferred, based on their slightly convex-upward morphology, and position along the margins of the valley in widening reaches downstream from debris-flow producing tributaries [*Carling*, 1989]. Wide floodplains also have developed in reaches whose downstream ends are constricted by mass movements. Reaches with extensive floodplain surfaces (LD, LE, LF, and FE) have developed in response to earthflow constriction of a downstream reach (LC in Lookout and FD in French Pete). Aggradation in upstream reaches is promoted both by constriction of the channel, which may hydraulically dam the upstream reach or physically block further downstream movement of debris flows, and by raised base level in the earthflow reach [*Vest*, 1988]. Floodplains may have once been more extensive in some reaches, such as LE, but have since become obscured by subsequent growth of alluvial fans. Large landslides may also override floodplain areas and limit their further development by narrowing the valley floor.

Terraces and alluvial fans. The proportion of valley floor width occupied by terraces and alluvial fans ranges from 18% (reach LF) to 85% (reach LA) and displays no consistent relationship with valley floor width index (Figure 6, Table 3). Factors contributing to long-term preservation

TABLE 3. Average Widths of Surfaces By Reach for French Pete and Lookout Creek Sites

	Active Channel (m)	Secondary Channel (m)	Floodplains 1964 and Younger (m)	Floodplains Pre-1964 (m)	Terrace (m)	Fan (m)	Total Width 1964 and Younger Surfaces (m)	Total Width Valley Floor (m)	Proportion of Valley Floor Reset By 1964 Flood
FRENCH PETE CREEK									
FA	18.7	8.8	5.0	14.2	36.5	13.1	32.4	46.6	70
FB	18.2	1.5	3.6	1.5	25.3	22.5	23.4	24.9	94
FC	15.3	6.0	5.1	21.5	3.5	16.5	26.4	47.9	55
FD	24.3	2.5	4.4	0.7	3.6	13.5	31.3	32.0	98
FE	20.7	5.6	12.4	30.6	16.9	21.7	38.7	69.3	56
FF	20.3	3.2	3.0	8.7	16.9	13.3	26.5	35.2	75
LOOKOUT CREEK									
LA	14.3	0.3	5.2	4.6	23.6	114.5	19.7	24.3	81
LB	20.5	3.4	6.4	30.6	29.4	78.4	30.3	60.9	50
LC	15.8	0.3	4.2	5.1	2.8	8.1	20.3	25.4	80
LD	36.4	9.1	15.2	105.4	30.1	43.4	60.6	166.0	37
LE	14.9	0.0	17.3	26.7	6.1	178.6	32.3	58.9	55
LF	32.1	11.7	27.8	40.4	9.1	14.8	71.6	112.0	64

Widths calculated by dividing total area in each surface type by reach length.

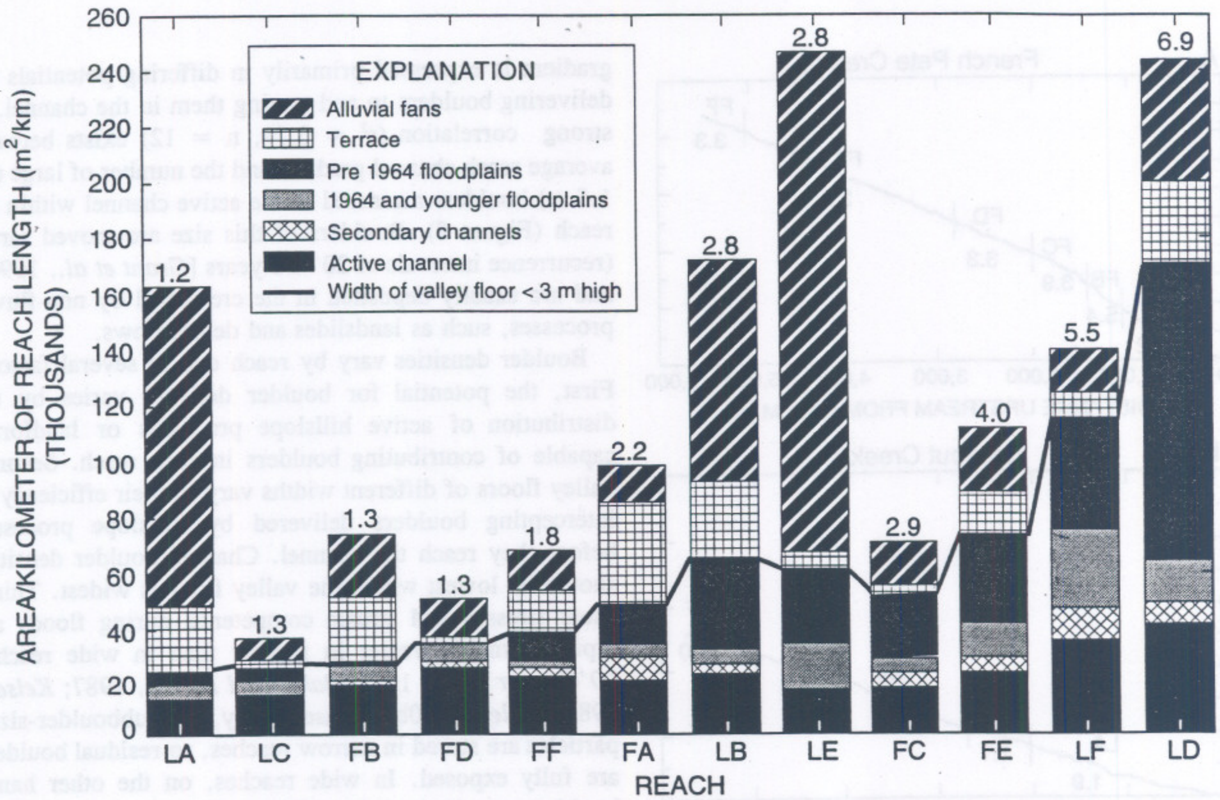

Fig. 6. Distribution of valley floor surfaces by reach for both sites ordered by valley floor width index (shown above bars). Reaches were identified by a two-letter code, where the first letter denoted the site (F = French Pete Creek, L = Lookout Creek) and the second denoted the order of the reach (A = furthest downstream, F = furthest upstream). Vertical axis is the total area by reach in each surface type divided by the reach length.

of terrace and fan deposits are complex, including location and orientation of these features in relation to the active channel, erodibility of deposits, and in the case of fans, whether they are actively growing by debris-flow deposition. More extensive fans in Lookout Creek reflect the wider valley floor (outside the zone measured by the VFWI and including terraces and fans), which allowed fans to develop and survive erosion by the mainstem channel.

Overall trends in landform distribution. Two points stand out from this analysis. First, while it is intuitively obvious that wider landforms are found on wider valley floors, not all surface types contribute equally to increasing valley width in montane valley floors (Figure 6). In general, increasing valley floor width is accommodated primarily by increasing width of floodplains. Taking both young and older floodplains together, this increase appears to be nonlinear for the limited sample size reported here. This suggests that as valleys widen, the proportion of valley floor in floodplains may increase sharply where the ratio of valley to channel width exceeds four. A second point is that the width of valleys and associated landforms in mountain streams is not controlled by the discharge alone, which is relatively constant over the short reach lengths examined here, but by the distribution of hillslope processes and resistant channel margins impinging on the valley floor.

5. VARIATION IN CHANNEL GRADIENT AND BOULDER DENSITIES BY REACHES

We examined the longitudinal profiles of the two creeks to determine whether the pattern of reaches defined by valley floor width also were reflected in the channel gradient. The longitudinal profiles of the two creeks through the two study sites are relatively straight (Figure 7). There is a weak (r^2 = 0.15, n = 12) negative correlation between valley floor width index and average channel gradient by reach; so narrow reaches tend to be steeper than wide reaches. The convexity in channel gradient in the French Pete profile corresponds to reach

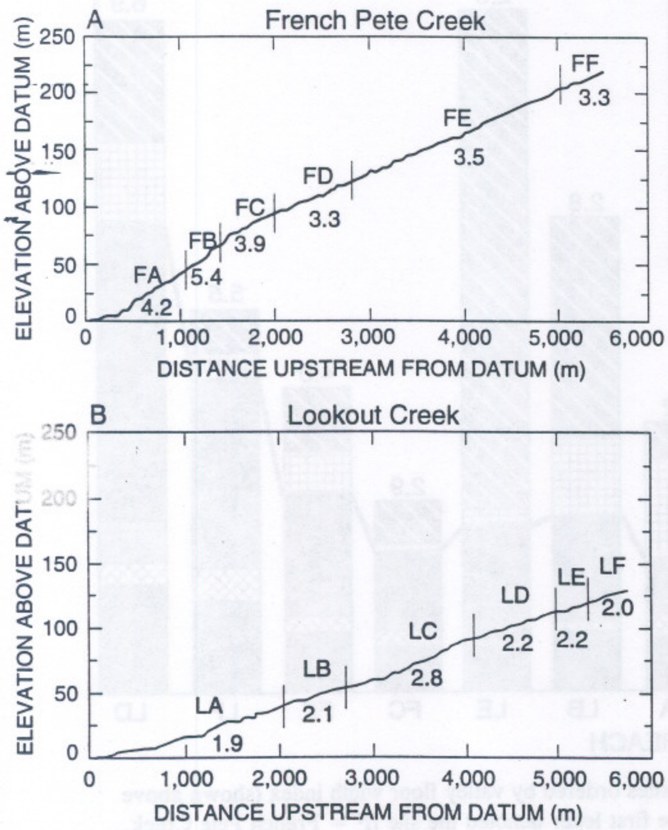

Fig. 7. Longitudinal profiles of the two study sites showing reach boundaries. (a) Lookout Creek. (b) French Pete Creek. Numbers show average channel gradient (in percent) by reach.

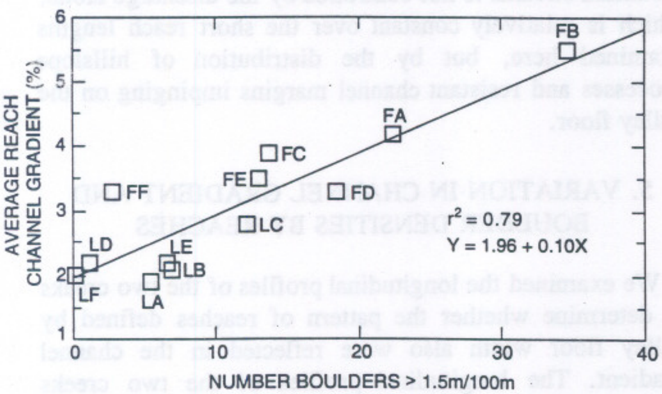

Fig. 8. Relation between average channel gradient and average boulder densities by reach.

FC, and the concavity in the Lookout Creek profile corresponds closely with reach LC.

The influence of reach-forming processes on channel gradient is expressed primarily in differing potentials for delivering boulders to and storing them in the channel. A strong correlation ($r^2 = 0.79$, $n = 12$) exists between average reach channel gradient and the number of large ($\geq$ 1.5 m) boulders measured in the active channel within the reach (Figure 8). Boulders of this size are moved rarely (recurrence intervals of 20 - 50 years [*Grant et al.*, 1990]) and are usually deposited in the creek bed by non-fluvial processes, such as landslides and debris flows.

Boulder densities vary by reach due to several factors. First, the potential for boulder delivery varies by the distribution of active hillslope processes or landforms capable of contributing boulders in each reach. Second, valley floors of different widths vary in their efficiency in intercepting boulders delivered by hillslope processes before they reach the channel. Channel boulder densities should be lowest where the valley floor is widest. Third, shear stresses and stream competence during floods are typically much greater in narrow than in wide reaches [*O'Connor et al.*, 1986; *Baker and Pickup*, 1987; *Kelsey*, 1988; *Miller*, 1990b]. Consequently, few subboulder-sized particles are stored in narrow reaches, so residual boulders are fully exposed. In wide reaches, on the other hand, boulders may be buried by finer sediments.

Boulder densities (number of boulders $\geq$ 1.5 m in diameter per 100 m along the channel axis) were analyzed for each study stream, because the overall boulder density in French Pete Creek (16.6) was significantly higher than in Lookout Creek (6.2). Highest boulder densities occur in both sites where the channel is bordered by deeply incised alluvial fans and terraces underlain by old debris-flow deposits (FB, FA) and along earthflow-dominated reaches (FD, LC) (Table 2). Boulder densities are lowest in wide, fan-constrained reaches (LD, LF) where the wide valley floor permits development of large, active fans. Within-fan sorting of material supplied from tributaries leads to boulder deposition near fan apexes and finer sediment deposited near distal margins of fans proximal to channels. Hence, few boulders are visible in channels adjacent to fans developed on wide alluvial floors. Extensive deposits of finer gravels and cobbles in reach LD may also have buried boulders. In both sites, boulder densities decrease with valley floor width index, approaching zero where the valley floor width index exceeds 6 (Table 2). Boulder densities are higher in French Pete as compared to Lookout Creek despite the greater proportion of channel length bordered by active mass movement processes (Table 2); this may reflect both longevity of boulders delivered to channels and prevalence of more competent lava flows and breccias in the French Pete basin [*Sherrod and Smith*, 1989].

6. VARIATION IN DISTURBANCE REGIMES BY REACH

The mosaic of valley floor landforms arrayed longitudinally along the stream reflects reach-to-reach differences in disturbances due to both fluvial and non-fluvial processes. The term "disturbance" is used in both its geomorphic and ecological sense as processes that either erode or create new landforms or remove riparian vegetation. To explore this, we examine the effects of the December 1964 storm in Lookout Creek, which varied by reach.

6.1 *Fluvial Disturbance*

Interpretation of the response of individual reaches to peak flows generated during the 1964 flood is limited by the fact that we can only observe the post-flood legacy of landforms and vegetation; we do not know what their distributions were prior to that event, since dense tree canopies precludes use of air photos. We can, however, infer what the magnitude of effects were by comparing the average total widths of landforms aged 1964 or younger, including the active channel and secondary channels, to the total width of the Holocene valley floor. The absolute width of valley floor reworked by the 1964 event is relatively constant up to a valley floor width index of 4.0 where it increases dramatically (Figure 6). However, the relative proportion of valley floor reworked by the 1964 storm decreases linearly with valley floor width index (Table 3). In some reaches (i.e., FB, FD, LA, LC), over 80% of the landforms on the valley floor are less than 30 years old; while in other reaches (i.e., LD), young valley floor represents only 37% of the total.

Reach-to-reach differences in hydraulic forces generated by the 1964 storm are probably responsible for these trends (Table 4). Shear stresses exerted on the bed by flood flows are much higher in narrow, constrained reaches than in wide, unconstrained reaches. The reach-level planform geometry of the valley floor strongly controls the pattern of erosion, deposition, and disturbance to riparian vegetation during major flood events. Where streams are confined by steep valley walls, high terraces, fans, landslide colluvium, or bedrock (LA, LB, LC, LE), flows are deep and channel gradients are higher than average; so shear stresses are high, and erosion of banks and surfaces and uprooting of riparian vegetation are dominant processes. Landforms created or reworked in these reaches are likely to be narrow (Figure 6). On the other hand, where the valley is wide relative to channel width (LD, LF), shear stresses are lower and deposition and lateral channel changes are dominant processes. Deposits from previous floods are less likely to be disturbed; so wide floodplains with diverse age classes of vegetation and sediment are preserved (Figure 6). The distribution of floodplain surfaces older than 1964 also follows the trend of increasing width with decreasing shear stress (Table 4, Figure 6), suggesting that control of erosion and deposition by valley floor geometry persists over long timescales.

Similar patterns have been reported elsewhere [*Wolman and Eiler,* 1958; *Nanson,* 1986; *O'Connor et al.,* 1986; *Baker and Pickup,* 1987; *Kelsey,* 1988; *Jacobson et al.,* 1989; *Miller,* 1990a, b; *Wohl,* 1992]. In particular, our data support Wolman and Eiler's observation [1958, p. 12] that scour of valley floors during floods is likely to occur where the channel occupies more than approximately one-third of the valley bottom. We plotted our reach data on their graph of the ratio of channel to valley width versus slope; the abscissa in this graph is the inverse of the valley floor width index to conform to their convention (Figure 9). All of the reaches showing significant deposition occur where the valley is greater than three channel widths wide. Although we examined only a limited range of slopes, there was no discernible trend with gradient, as suggested by the Wolman and Eiler curve. We suggest that the ratio of channel to valley width alone accounts for most of the difference in whether floods scour or deposit, by determining the height of the floodwaters, hence shear stress. As *Wolman and Eiler* [1958] point out, however, narrow valleys and steep slopes tend to be associated in nature; so distinguishing the relative importance of slope versus width may be difficult.

6.2 *Non-fluvial Disturbance*

Reaches also differ in their susceptibilities to disruption by non-fluvial disturbances, such as debris flows and landslides. In the case of landslides, susceptibility is related to the location of the reach with respect to sites of mass movement. Where earthflows impinge directly on the valley floor, valley floor surfaces and stream channels may experience episodic delivery of sediment and wood as toeslope areas oversteepen and fail [*Swanson et al.,* 1985]. These effects tend to be local, due to the large size and relative immobility of material delivered.

Four factors contribute to high susceptibility of reaches to debris flows: (1) presence of tributary source areas for debris flow within or immediately above a reach; (2) absence of impediments to debris-flow travel between tributary mouths and the channel, such as active fans or wide terraces or floodplains; (3) low junction angles that promote continued movement of material down the main stem [*Benda,* 1985]; and (4) abrupt decrease in gradient or

TABLE 4. Calculated Hydraulic Variables By Reach for the December 1964 Flood in Lookout Creek

Reach	Q*	n**	Slope	Width of 1964 Inundated Surface***	Calculated hydraulic radius (R)†	Shear Stress (τ)††
	(m^3/s)		(m/m)	(m)	(m)	(N/m^2)
LA	179	0.051	0.019	19.7	2.1	380
LB	157	0.052	0.021	30.3	1.5	300
LC	150	0.055	0.028	20.3	1.7	470
LD	136	0.045	0.022	60.6	0.8	170
LE	128	0.052	0.021	32.3	1.2	250
LF	124	0.040	0.020	71.7	0.7	130

*Discharges (Q) were calculated by reach by assuming a linear relationship between drainage areas and the discharge measured at the U.S.G.S. gaging station at 63 km^2 (187 m^3 s) and determining the drainage area at the midpoint of each reach.

**Manning's roughness coefficients (n) were determined from *Barnes* [1967] for the roughest and least rough reaches (LC and LF, respectively), based on boulder density and other observations and the remainder of the reaches assigned a roughness coefficient from a linear regression of the log-transformed relation between boulder density and roughness for these two reaches.

***Sum of the widths of post-1964 age surfaces, including active channel, secondary channel, and 1964 and younger floodplains (Table 3). This assumes that this entire set of surfaces were occupied by flow at the same time.

†Calculated from the continuity equation Q = W*D*V and the Manning's equation $V = (R^{0.67}S^{0.5})/n$, where Q is discharge (m^3 s), W is width (m), D is depth (m), and V is velocity (m/s), R = hydraulic radius, S = friction slope, and n = Manning's roughness coefficient. Assuming that S = bed slope, substituting R for D and solving for R gives $R = [(Qn/WS^{0.5})]^{0.60}$

††Total boundary shear stress τ calculated as $\tau = \gamma RS$, where γ is the specific weight of water.

widening of the valley that promotes debris-flow stoppage. Actual transport of material down the mainstem may not be as a true rheological debris flow but as a debris-laden flood pulse, particularly if full or partial damming of the mainstem triggered a dam outburst flood [*Costa and Schuster*, 1988; *Costa*, 1988].

From these considerations, we would predict that debris flows entering narrow reaches at the head of wide reaches may result in the greatest riparian disturbances (Figure 10a). Debris flows entering directly into wide reaches may rapidly lose energy and mass and may not have sufficient volume to block the channel (Figure 10c). Debris flows into long, narrow reaches can only disturb the narrow floodplains found there (Figure 10b). This is borne out in comparing the extensive 1964-age floodplains, including debris-flow deposits, in wide reaches FE and LD with the very limited floodplains and debris-flow deposits of the same age in reaches LA, LB, and LE despite the latter reaches experiencing runout from nine separate debris flows during the 1964 storm (Figure 3a, b).

7. CONTRASTS BETWEEN VALLEY FLOORS IN LOW- AND HIGH-GRADIENT SYSTEMS

Comparing surficial morphology of valley floors in mountain and low-gradient streams is useful to highlight differences in dynamics between these two systems. Few published data, however, provide a basis for such a comparison [*Swanson and Sparks*, 1990]. In a study section of the Little Missouri River [*Everitt*, 1968], for example, the river has reworked a valley floor area of approximately 5.9 channel widths in lateral extent (0.54 km^2 of valley floor per km of valley length) in the century before Everitt's analysis. This meandering river section has low slope (0.00085) and an extensive history of channel change recorded in cottonwood forest up to 300 years old.

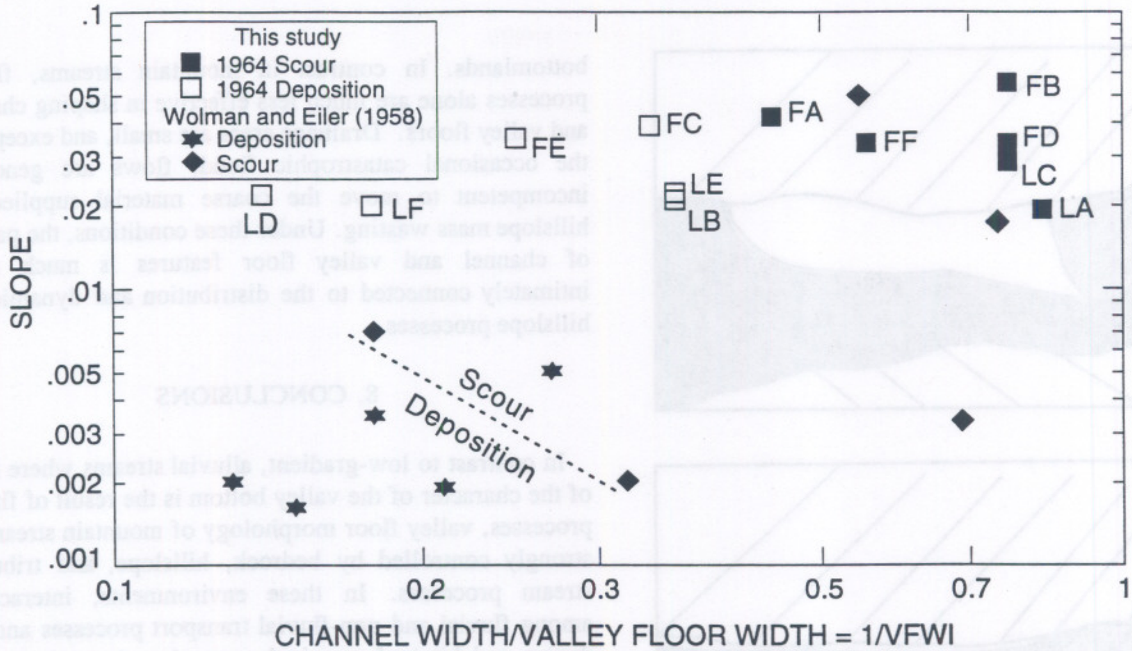

Fig. 9. Patterns of scour and deposition during floods in relation to channel gradient and the ratio of channel width to valley floor width, after *Wolman and Eiler* [1958]. Shown are Lookout and French Pete Creek reaches and data points for the Connecticut River following the 1955 flood. The dotted line is Wolman and Eiler's [1958] envelope curve (fitted by eye) distinguishing domains of scour and deposition for their data.

In French Pete and Lookout Creeks, by comparison, the area that has been fluvially reworked in the past century ranges by reach from 1.3 to 2.1 channel widths (0.023 to 0.039 km^2 of valley floor per km of valley length) in French Pete and 1.0 to 3.3 channel widths (0.020 to 0.072 km^2 of valley floor per km) in Lookout Creek. These values are calculated using the widths of active channel plus 1964 and later floodplains; this assumes that virtually all channel changes in the past 100 years occurred during the 1964 storm. Recently published analyses of long-term cross-section data from Lookout Creek confirms that very little change in cross-section area occurs between major storms [*Nakamura and Swanson,* 1993]. Constraint by bedrock, landslides, steep hillslopes, high gradients, and coarse channel beds limit the extent of valley floor reworking.

The rate and geometry, as well as the lateral extent, of channel change are different in the two systems. *Everitt's* [1968] dendrochronologic analysis of cottonwood forest indicates that channel change has been progressive, not episodic: arcuate bands of forest of increasing age defining old point bars generally trend away from the channel towards the edge of the valley floor. In French Pete Creek and Lookout Creek, on the other hand, the only conspicuous forest age class colonizing fluvial surfaces is of 1964 origin and parallels the channel. Older forest along valley floors generally exceeds 100 years in age and originated following wildfire [*Teensma,* 1987].

From this analysis, we infer that valley floor change in lowland, meandering streams is dominated by higher frequency, lower magnitude events, and the areal extent of change at the century time scale is greater than in mountain streams. The implication of this is twofold. First, the pattern of vegetation emphasizes that rare events are needed to sculpt the bottomland morphology in mountain streams. Second, due to the limited opportunity for change in steepland valley bottoms, the same reaches of the stream network are repeatedly and episodically disturbed. Consequently, the flood record, as preserved in stratigraphy and vegetation, is much less complete than in lowland streams.

What emerges from this comparison with *Everitt's* [1968] work is that a key difference between mountain and lowland streams is the relative importance of fluvial versus non-fluvial processes in determining channel and valley floor morphology. In lowland streams, channel and valley floor features are created and maintained by the interaction among flow hydraulics, sediment transport, and the channel boundaries; bankfull and higher flows that occur relatively frequently are the dominant geomorphic agents shaping

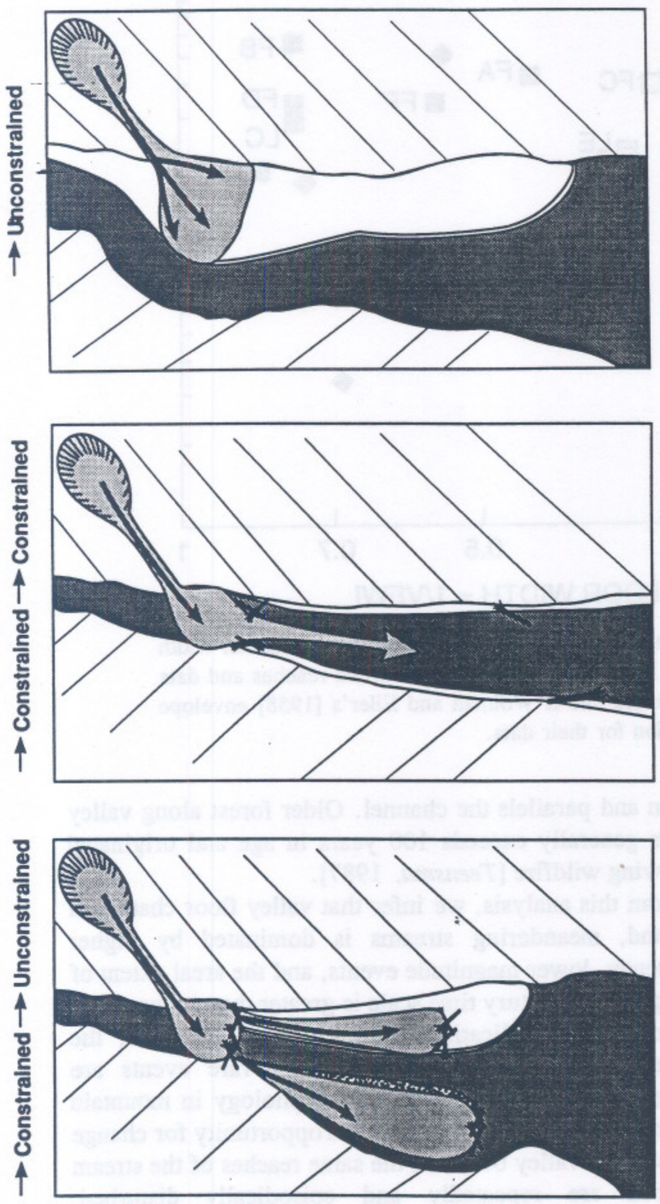

Fig. 10. Hypothesized differences in downstream disturbance potential for debris flows entering mainstem channels, depending on degree of constraint in receiving channel and downstream reach morphology. (a) Debris flow enters constrained reach situated immediately upstream of unconstrained reach. Potential for debris flow to temporarily dam creek leading to dam-break flood and major deposition and reworking of downstream surfaces is high. (b) High shear stresses and limited opportunity for sediment storage in constrained reach below debris-flow entry point limits potential for valley floor disturbance. (c) Wide valley floor surfaces in unconstrained reaches can trap debris-flow material before it reaches channel.

bottomlands. In contrast in mountain streams, fluvial processes alone are much less effective in shaping channel and valley floors. Drainage areas are small, and except for the occasional catastrophic flood, flows are generally incompetent to move the coarse material supplied by hillslope mass wasting. Under these conditions, the pattern of channel and valley floor features is much more intimately connected to the distribution and dynamics of hillslope processes.

8. CONCLUSIONS

In contrast to low-gradient, alluvial streams where most of the character of the valley bottom is the result of fluvial processes, valley floor morphology of mountain streams is strongly controlled by bedrock, hillslope, and tributary stream processes. In these environments, interactions among fluvial and non-fluvial transport processes and the degree and kind of marginal constraints determine valley floor width. Differences in valley floor width are expressed in a reach-to-reach variation in distribution of geomorphic surfaces of different types, modes of origin, ages, and geometries arrayed along the channel. Hillslope processes dominate channel morphology and disturbance regime of the valley floor. Processes creating surfaces in narrow montane valleys episodically restructure valley bottoms, preserving only a fraction of the stream's history.

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