

# Distribution of bedrock and alluvial channels in forested mountain drainage basins

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MOUNTAIN river networks often consist of both bedrock and alluvial channels<sup>1-5</sup>, the spatial distribution of which controls several fundamental geomorphological and ecological processes<sup>6,7</sup>. The nature of river channels can influence the rates of river incision and landscape evolution<sup>1,2</sup>, as well as the stream habitat characteristics affecting species abundance and aquatic ecosystem structure<sup>8-11</sup>. Studies of the factors controlling the distribution of bedrock and alluvial channels have hitherto been limited to anthropogenic badlands<sup>12</sup>. Here we investigate the distribution of channel types in forested mountain drainage basins, and show that the occurrence of bedrock and alluvial channels can be described by a threshold model relating local sediment transport capacity to sediment supply. In addition, we find that valley-spanning log jams create alluvial channels—hospitable to aquatic life—in what would otherwise be bedrock reaches. The formation of such jams depends critically on the stabilizing presence of logs derived from the largest trees in the riverside forests, suggesting that management strategies that allow harvesting of such trees can have a devastating influence on alluvial habitats in mountain drainage basins.

The spatial distribution of bedrock and alluvial reaches depends on the relation of local transport capacity ( $q_c$ ) to the bedload sediment supply ( $q_s$ ) delivered from upstream and across channel banks. A bedrock stream bed indicates a transport capacity in excess of sediment supply ( $q_c > q_s$ ), whereas an alluvial stream bed indicates either a balance or an excess of sediment supply ( $q_c \leq q_s$ ) (refs 13,14). A general expression for sediment transport capacity incorporating both drainage area,  $A$ , and channel gradient,  $S$ , is  $q_c = kA^m S^n$ , where  $m, n > 0$  and  $k$  is an empirical variable<sup>15</sup>. In drainage basins with relatively uniform geology, hydrology and vegetation, the sediment supply to a channel reach can be expressed as  $q_s = bA^p$ , where  $b$  and  $p$  are empirical variables. Local conditions can cause substantial deviations in either  $q_c$  or  $q_s$  from basin-wide trends. The critical gradient,  $S_c$ , for  $q_c = q_s$  may be expressed as

$$S_c = [(b/k)A^{p-m}]^{1/n} \quad (1)$$

in which  $b, k, p, m$  and  $n$  incorporate local transport capacity, sediment supply characteristics, geology and climate. This critical-slope model therefore predicts that bedrock channels occur where  $S > S_c$ , and alluvial channels occur where  $S \leq S_c$ . We tested this model against data from field surveys in the Satsop River basin, Washington.

The Satsop River originates in Tertiary basalts in the Olympic mountains, flowing southward over Tertiary marine sandstone and siltstone and Pleistocene till and outwash<sup>16,17</sup> to join the Chehalis River and empty into the Pacific Ocean through Grays Harbor. The study area receives ~2,500 mm of annual rainfall<sup>18</sup> and lies in the *Tsuga heterophylla* vegetation zone<sup>19</sup>. Extensive early twentieth century logging removed the prehistoric forest and industry now harvests naturally regenerated forest. As in most of the Pacific Northwest, early logging practices significantly disturbed stream channels<sup>20</sup>, and aggressive programs intended to improve fish habitat removed logs from channels in the 1950s through to the 1980s (ref. 21). Extensive salvage of large cedar logs

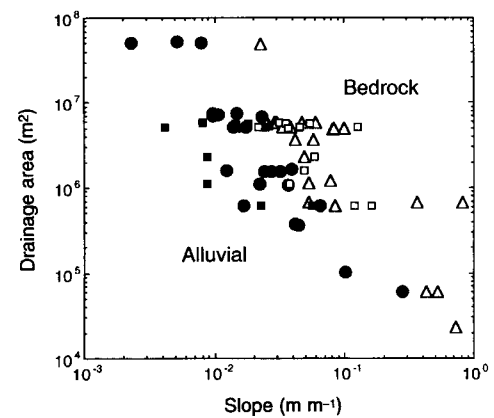


FIG. 1 Plot of drainage area versus reach-average slope for channels in the study area. Larger data points represent channel reaches lacking log jams; open triangles indicate bedrock reaches and solid circles represent alluvial reaches. Smaller data points are from reaches with channel-spanning log jams; solid squares represent forced alluvial reaches immediately upslope of valley-spanning log jams and open squares represent the slope of the underlying bedrock surface, and hence the estimated reach slope in the absence of these jams.

further diminished the supply of in-channel large woody debris over this same period.

We surveyed continuous topographic profiles down stream-bed centrelines in 59 reaches of the West Fork Satsop River and several tributaries using either a hand-level or tripod-mounted autolevel, rod and tape. We subdivided channels into bedrock or alluvial reaches ranging between 10–20 channel-widths in length, with reach-average slopes and bank full-widths of 0.0023 to 0.81 and 1 to 46 m, respectively. As considered here, bedrock reaches exhibit alluvial cover over lengths of less than a channel width, and alluvial reaches exhibit bedrock exposures of at most a channel width in length. Occasional mixed-morphology reaches with alternating bedrock and alluvial bed surfaces extending downstream for more than a channel width do occur in the study area, but were excluded from this study. We mapped bed morphology and the extent of alluvial terraces and flood plains along two tributaries onto a 1:4,000 scale map of channel thalwegs surveyed using a laser level. We also mapped reach locations onto US Geological Survey 1:24,000 scale topographic maps, from which we determined drainage areas (ranging from 0.02 to 52 km<sup>2</sup>) using a digital planimeter.

Slopes of bedrock reaches exceed those of alluvial reaches with comparable drainage areas (Fig. 1). A threshold separating bedrock and alluvial data is well described by an inverse area dependency to the critical slope, predicted by equation (1) for  $m > p$ . Whereas bedrock channels theoretically plot anywhere above the bedrock/alluvial threshold, non-aggrading alluvial channels would be expected to plot close to the threshold. Thus, scatter within the free-formed alluvial channels may imply that reaches with lower slopes will continue to aggrade until  $S = S_c$ . Alternatively, such scatter records the magnitude of local variability in sediment supply and transport capacity. Some surveyed reaches showed evidence of recent shallow landsliding from valley walls, and differences in channel confinement may impose local variability to transport capacity. Variance of the alluvial data may also reflect bed armouring and variations in roughness due to large woody debris, which can significantly reduce the transport capacity of forest channels<sup>22</sup>. The threshold shown in Fig. 1, however, indicates that such effects are a secondary influence on the spatial distribution of bedrock and alluvial reaches in the Satsop River basin.

Several processes may transiently affect the distribution of bedrock reaches in mountain drainage basins. Scour by debris flows, for example, can intermittently convert alluvial reaches to a

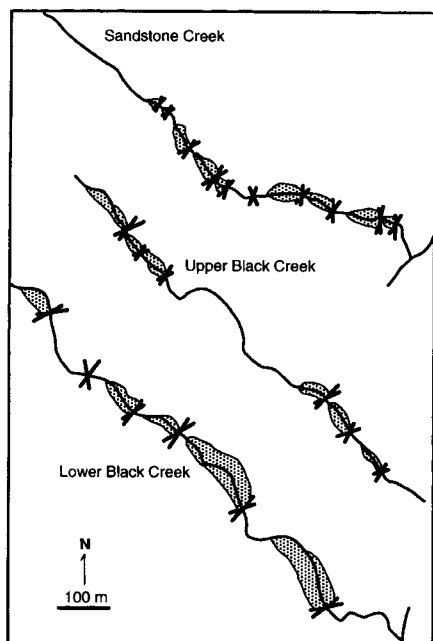


FIG. 2 Maps of southeast-flowing Black and Sandstone creeks showing the distribution of log jams (crosses) and alluvial terraces (stippled).

bedrock morphology. Episodic disturbance such as landslides may introduce and route sediment pulses through mountain channel networks, temporarily converting bedrock reaches to alluvial morphologies<sup>23</sup>. We anticipate that spatial and temporal variations in sediment supply could complicate relations of the kind reported here; local sources of high sediment supply could result in alluvial reaches within the field of bedrock data and locally reduced supply, or increased transport capacity could likewise result in bedrock reaches within the field of alluvial data. Such exceptions to the critical-slope model may prove valuable in interpreting watershed history and conditions, a central focus of watershed analysis efforts in the Pacific Northwest<sup>24</sup>.

The introduction of large woody debris can significantly influence channel morphology and aquatic ecosystems in forested environments<sup>25-27</sup>. Individual logs and log jams can dominate pool and bar formation<sup>27-30</sup> and control the local elevation drop in steep forest channels<sup>31,32</sup>. Alluvial terraces and flood plains along surveyed tributaries of the West Fork Satsop River occur as backwater deposits immediately upstream of naturally occurring, valley-spanning log jams (Fig. 2); small terrace remnants lie upslope of both of the breached log jams that lack mappable alluvial deposits. Alluvial deposits, side channels and pools associated with these jams provide aquatic habitat unavailable in bedrock channels.

Longitudinal channel profiles indicate that physical obstruction to sediment movement and backwater effects associated with valley-spanning log jams force deposition of alluvium in otherwise bedrock reaches. In each reach with a valley jam, slopes were determined for the alluvial stream beds immediately upslope of the jam. Bedrock exposed at the base of surveyed jams and in upstream pools allowed determination of the average gradient of the underlying bedrock surface. These data reveal that log jams can force active alluvial beds in otherwise bedrock reaches (Fig. 1) and indicate that jam removal would convert these forced alluvial channels into bedrock reaches. In these mountain channels, the distribution of stable log jams dominates the distribution of alluvial channel reaches.

Individual large logs, in turn, govern the stability of valley-spanning log jams. Field observations demonstrate that the key member logs<sup>27</sup> anchoring the surveyed jams are old-growth remnants and large second-growth trees. Diameters of key members

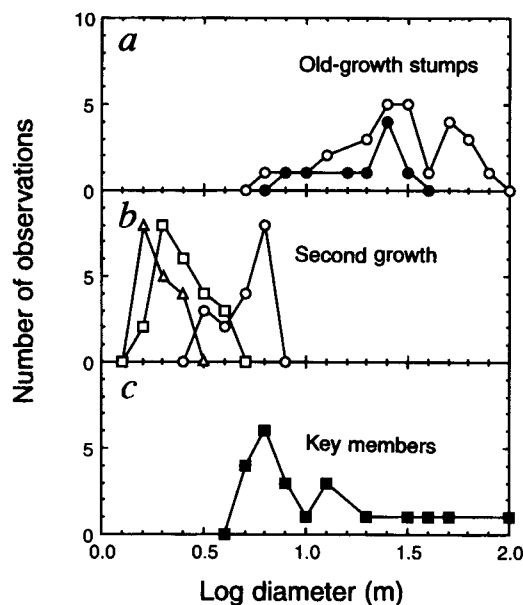


FIG. 3 Frequency distribution of a, the diameter of old-growth stumps in the riparian zone; b, trees in the current riparian forest; and c, key member logs that stabilized valley-spanning log jams. Circles, Douglas fir; filled circles, cedar; squares, hemlock; triangles, alder; filled squares, logs of any species acting to anchor jams (key members).

exceed those of all but the largest trees in second-growth riparian forests, but closely correspond to those of prehistoric riparian stumps (Fig. 3). Streamside forest management involving removal of the largest trees and retention of smaller ones<sup>33,34</sup> therefore favours long-term conversion of alluvial reaches to bedrock in those portions of mountain drainage basins where  $S > S_c$ .

The observation that bedrock channels occur on steeper slopes than alluvial channels of comparable drainage area implies an excess transport capacity that should render bedrock channels relatively insensitive to changes in sediment supply or discharge<sup>35</sup>. Reaches plotting close to the bedrock/alluvial threshold, however, likely represent channels particularly susceptible to land use impact or climate change. Channel networks with short, mixed alluvial and bedrock reaches where  $S \approx S_c$  could respond dramatically to even modest changes in sediment supply, discharge or the input of large logs. Our findings support the use of a critical-slope model to discriminate bedrock and alluvial channels in landscape evolution models and suggest the potential for basin-wide predictions of channel type based on limited field surveys. Our results imply that removal of in-stream logs could have devastated much of the upland alluvial habitat in portions of mountain drainage basins in the Pacific Northwest. Furthermore, the large diameter of key member logs currently stabilizing valley-spanning jams implies that persistence of alluvial channel reaches in mountain streams can depend on the presence of old-growth-sized trees. Even the selective harvest of the largest trees in streamside forests may entail profound long-term impacts on aquatic ecosystems in forested mountain drainage basins. □

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