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Geomorphic coupling of hillslope and channel systems in two small mountain basins

by

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with 3 figures, 2 photos and 5 tables

Zusammenfassung   Sedimentbilanzen für zwei kleine (10 ha) gebirgige Einzugsgebiete, eines in der westlichen Cascade Range von Oregon, das andere in den Colorado Rocky Mountains, werden hier dargelegt. Prozesse an Hängen und im Fluß wurden durch ähnliche Methoden über 5–6 Jahre gemessen, und die absoluten Raten der geomorphischen Aktivität und die relative Bedeutung der unterschiedlichen können verglichen werden. Daraus ergeben sich drei wesentliche Unterschiede im Verhalten der zwei Systeme: 1. Raten der geomorphischen Aktivität im Cascade Einzugsgebiet sind 10mal so groß wie die im Rocky Mountain Gebiet. 2. Die Anlieferung des Materials zum Fluß in den Cascaden wird durch episodische Schuttströme dominiert mit einer Periodizität von etwa 400 Jahren. Im Gegensatz dazu wird das Material zum Colorado Gebirgsfluß in Lösung oder durch nicht katastrophale Massenbewegungen angeliefert. 3. Eine ungefähre Bilanz zwischen Sedimentanlieferung zum Fluß und Export aus dem Einzugsgebiet scheint in dem Cascade-Beispiel zu bestehen, während im Rocky Mountain-Beispiel nur etwa 10% des zum Fluß angelieferten Materials auch exportiert wird. Damit verhält sich ersteres als „Landschaft im Gleichgewicht", während das zweite einem „Zerfallsmodell" der Landschaftsentwicklung entspricht (THORNES & BRUNSDEN 1977).

Summary. Sediment budgets for two small (10 ha area) mountain catchments, one in the western Cascade Range of Oregon, the other in the Colorado Rocky Mountains, are presented here. Hillslope and stream processes have been measured by similar procedures over 5–6 years and so the absolute rates of geomorphic activity and the relative importance of different processes can be compared. This suggests three important contrasts in the behavior of the two systems. (1) Rates of geomorphic activity in the Cascade catchment are 10× greater than those in the Rocky Mountain basin. (2) Delivery of material to the stream channel in the Cascades is dominated by episodic debris flows with a periodicity of about 400 yr. In contrast, material is delivered to the Colorado mountain channel in solution or by non-catastrophic mass wasting. (3) An approximate balance between sediment delivery to the stream channel and export from the basin occurs in the Cascade case whereas the Rocky Mountain catchment exports only about 10% of the sediment delivered to its stream channels. Thus, the first behaves as an "equilibrium landscape" whereas the second corresponds to a "decay model" of landscape development (THORNES & BRUNSDEN 1977).

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Résumé. Des bilans sédimentaires sont presentés pour deux petite bassins, l'un de l'ouest de la chaîne des Cascades en Oregon, l'autre des Montagnes Rocheuses au Colorado. La pente des versants et les processus de courant ont été mesurés par des procédés similaires pendant 5 à 6 ans, si bien que les degrés absolus d'activité géomorphologique et d'importance relative des différents processus peuvent être comparés. Ceci suggère trois contrastes importants dans le comportement des deux systèmes. (1) Les degrés d'activité géomorphologique dans le bassin des Cascades sont dix fois plus grands que ceux des Montagnes Rocheuses. (2) L'apport de matériaux auch chenal dans les Cascades est dominé par des coulées épisodiques de débris avec une récurrence d'environ 400 ans. Par contre dans le Colorado, les matériaux sont apportés au chenal soit en solution, soit par des mouvements de masse non catastrophiqaues. (3) Dans le cas des Cascades, il existe un équilibre approximatif entre l'apport de sédiments au chenal et l'évaluation du bassin tandis que dans le bassin des Montagnes Rocheuses le chenal n'évacue que 10% des matériaux qui y sont apportés. Ainsi, le premier se comporte comme un "equilibrium landscape", tandis que le second corrspond à un "decay model" de développement de paysage (THORNES & BRUNDSEN 1977).

Introduction

The continued emphasis on research into material flows and budgets in ecology and geomorphology is often based on the assumption that discharges from a catchment represent simple, integrated responses to processes acting within it (e. g. BORMANN & LIKENS 1967). This is obviously not the case with organic materials and labile substances that are cycled or stored internally (CUMMINS et al. 1983). Equally, it may not be valid for less reactive materials, such as most clastic sediments, which are frequently stored within stream basins for very long periods.

Sediment delivery ratios (SDR) (the ratio of channel yield to the volume of material mobilized in a basin) have been used to deal with imbalances in sediment routing systems which are treated as "black boxes" (SCHUMM 1977). The apparent loss of sediment between its source and a downstream sampling site, which gives a SDR of less than 1.0, is commonly attributed to net storage within the fluvial system. The SDR and associated concepts have been most often applied in landscapes where material flux is dominated by overland flow and fluvial sediment transport (e. g. TRIMBLE 1975).

In this paper, the estimation of sediment budgets within small mountain basins allows us to examine separately the delivery ratios for hillslope (as the ratio of mass delivery to the channel vs mass mobilized on the slopes) and channel (as the ratio of mass export through the channel vs mass delivery to it) processes. Thus, our treatment extends beyond the usual estimates of input and output and includes an evaluation of the efficiency of the coupling between slope and channel systems in low order (STRAHLER 1957) basins. This is a critical boundary in the transfer of material and energy in ecologic and geomorphic systems.

Study sites

Two sites in the Long-Term Ecological Research (LTER) network (CALLAHAN 1984; BHOWMIK 1987; SWANSON & FRANKLIN 1988) allow comparison: Watershed 10 on the H. J. Andrews Experimental Forest (Western Cascade Range, Oregon) and the Martinelli catchment on Niwot Ridge (Colorado Rocky Mountains). They have

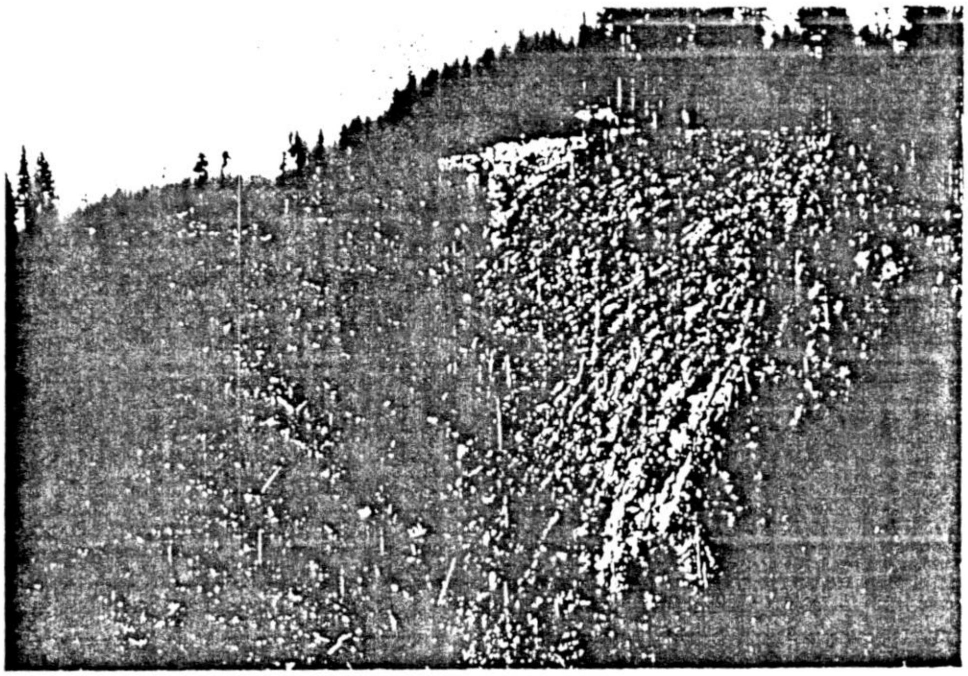

Photo 1. Watershed 10. Aerial view from the west into the upper part of the basin. Photographed in 1975 after clear cutting.

Table 1 Catchment characteristics.

	H. J. Andrews Watershed 10	Niwot Ridge Martinelli
Area (ha)	10.2	8.0
Channel length (m)	575	355
Drainage density (m/ha)	56.4	44.4
Channel area (m^2)	767	291
Average slope (°)	33	18
Channel slope (°)	10	10
Outlet elevation (m)	440	3415
Relief	220	185
Vegetation cover	Forest	Alpine turf/ Bare ground
Precipitation (mm)	2400	1050[1]
Rainfall (% of Ppt)	90	15
Runoff (mm)	1560	1492[2]

Notes:
[1] Pecipitation at Martinelli is the average for 1952–82 at D-1, 1.5 km west of the basin.
[2] Runoff from the Martinelli basin is the 1982–86 average. During this period, mean annual precipitation at D-1 was 1262 mm. The excess of runoff over precipitation is due to the concentration of snow in the basin by wind drifting.

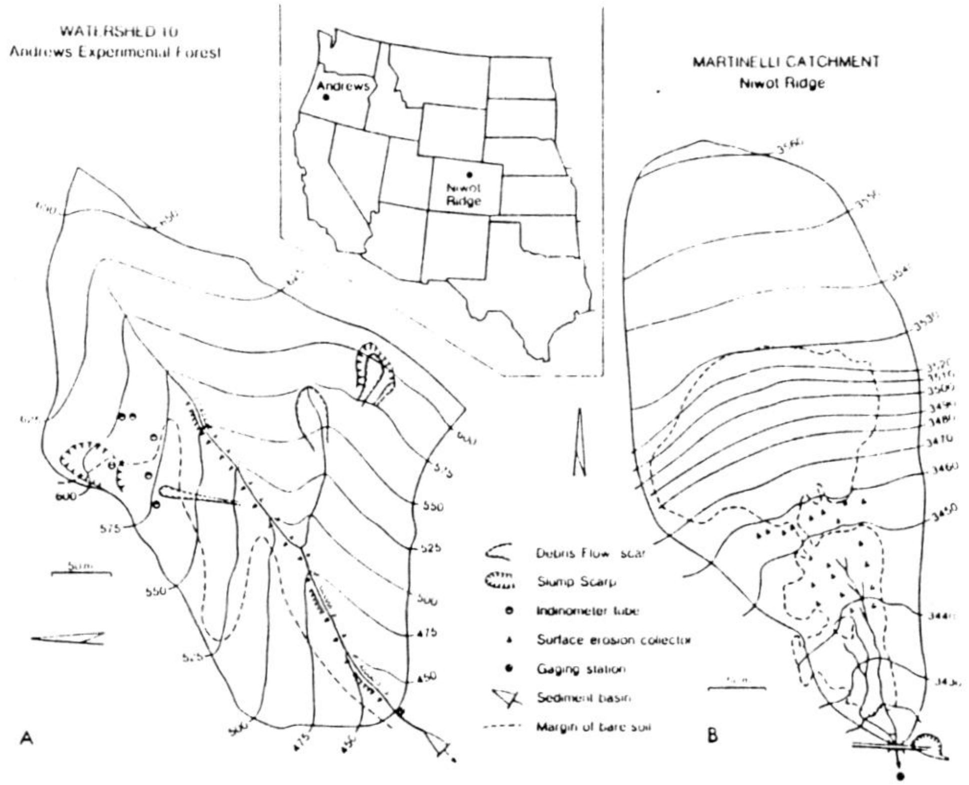

Fig. 1. The two field sites. A: Watershed 10, H. J. Andrews Experimental Forest, Cascade Range, Oregon. Elevations are in metres with a contour interval of 25 m. B: Martinelli Catchment, Niwot Ridge, Colorado Front Range. Elevations are in metres with a contour interval of 10 m.

equivalent area and topography (tab. 1), but differ markedly in terms of their valley-floor topography, vegetation, riparian condition, and late-Pleistocene history. These differences should be reflected in differences in their sediment budgets.

Watershed 10 (fig. 1) lies above 440 m elevation and shows no evidence of late-Pleistocene glaciation. SWANSON et al. (1982) define material fluxes within the basin and from it during 1969–1975 (and for a longer period for some geomorphic processes). Prior to clear cutting in 1975, an old-growth Douglas Fir forest which had been undisturbed for about 500 years controlled material transfer in the basin. Hillslopes in the basin are steep, almost rectilinear (photo 1) and uniformly covered by a colluvial mantle about 2.5 m thick. The stream system in Watershed 10 consists of a single well-defined channel with one tributary from the east side of the basin (fig. 1, photo 1) and carries perennial flow with a marked winter maximum.

The Martinelli Catchment lies above tree-line (3400 m) on the south side of Niwot Ridge in the Colorado Front Range (fig. 1) and was occupied by glacier ice

Photo 2. Martinelli Catchment. Aerial oblique from the east with the main part of the basin snow-covered, Spring 1982.

during the Pinedale (late-Pleistocene) glaciation. It is the head of a second order drainage fed primarily by meltwater from the snowpatch on the basin floor (photo 2). It is covered by a regolith at least two meters thick and bedrock is not exposed anywhere within it. In most years, almost half of the basin area is covered by snow until mid-summer and so supports no vegetation. The remaining area, largely on the drainage divides, has a ground cover of alpine turf. Except near the basin outlet, the channels on the colluvium are shallow and anastomosed, becoming more well defined near the basin outlet. At the beginning of summer, they are covered by up to 10 m of snow which exposes the channels as it melts. This means that the high discharges of early summer, when the channels are snow covered, are often not in direct contact with the channels exposed later in the season. So, these high flows have relatively little geomorphic effect.

Procedures

For both of these sites, the rates at which sediment is supplied to the stream channels by mass wasting and bank erosion have been estimated from direct observations over a 5–6 year period, augmented by retrospective inference of some processes for longer periods. Material yields from the basins have also been estimated by approximately equivalent procedures based upon flow records and sediment or solute concentrations. Although these results are not based on the same years (1969–75 in Watershed 10 and 1981–1986 at Martinelli), they are of comparable duration.

The procedures used to estimate sediment flux to the channel of Watershed 10 have been described by Swanson et al. (1982). Along the channel banks, 64 erosion boxes of 50 cm length were used to measure organic and inorganic material transported to the channel across the ground surface. Mass wasting processes, including soil creep, landsliding, and root throw were estimated from measurements within the basin and in similar forested environments elsewhere on the H. J. Andrews Experimental Forest. The use of a wide area effectively increases the sampling period for infrequent and catastrophic processes (Swanson et al. 1982).

Hydrologic conditions during the 1969–1975 period of direct measurement under old growth forest on Watershed 10 were about normal for the area and included no extreme droughts or floods.

At the Martinelli site, a similar approach to surface transport, in this case using 45 cm long traps, has been taken. Given the lack of vegetation cover when the ground is not covered with snow, surface erosion has received most attention (Caine 1976a). As in Watershed 10, the results of trap collections have been used to estimate supply to the stream channel by assuming the same rate of transport across the length of channel bank (twice the channel length) in the basin. Also as in Watershed 10, mass wasting and infrequent, high magnitude events are estimated from the larger area included in the studies of Benedict (1970) and Caine (1986).

The period of study at Martinelli has been one of above-normal snow accumulation which suggests that measured rates of sediment transfer might underestimate longer term responses because of the protective role of the snowcover (Caine 1976a). In contrast, removal of the snow cover in the basin occurred by early July in 1981, and was associated with highest rates of sediment flux observed in the basin.

Geomorphic activity

Hillslope processes

Geomorphic activity on the slopes of the two basins is summarized here in terms of the mass of material involved in movement and the geomorphic work which that movement represents (tab. 2). The latter, defined as the change in potential energy in the physical landscape, is included because it involves the distance of transport as well as the mass of sediment in motion (Caine 1976b).

When just the mass of material mobilized for slope transport is considered, the sediment budget for Watershed 10 is clearly dominated by soil creep processes, assumed to affect the colluvial layer over the entire catchment (tab. 2). By comparison, all other processes involve negligible volumes of material in any single year. However, this result is a partial product of the time base used in estimation. If the mass involved in motion were estimated over a decade or century, rather than a year, the soil creep estimate would change little, i. e. the same soil volume would be involved in all years. On the other hand, the mass affected by other processes would

Table 2 Hillslope activity in two mountain basins.

Mass in movement (tonnes/year)	Watershed 10		Martinelli	
	Inorganic	Organic	Inorganic	Organic
Solute transport	2.9 (> 0)	0.3 (> 0)	1.0 (> 0)	0.1 (> 0)
Surface erosion	800 (> 0)	450 (4)	859 (1)	23 (5)
Soil creep	270000 (99)	12500 (96)	60000 (95)	460 (92)
Solifluction	0	0	2500 (4)	15 (3)
Root throw	0.4 (> 0)	0.4 (> 0)	0	0
Debris flow	6.0 (> 0)	0.4 (> 0)	0	0
Total	270809	12950	63400	500

Geomorphic work (Joules $\times 10^{-6}$/yr)	Watershed 10		Martinelli	
	Inorganic	Organic	Inorganic	Organic
Solute transport	2.02 (24)	0.21 (24)	0.45 (32)	0.05 (93)
Surface erosion	0.46 (5)	0.26 (30)	0.08 (6)	0.002 (4)
Soil creep	0.48 (6)	0.02 (2)	0.17 (12)	0.001 (2)
Solifluction	0	0	0.70 (50)	< 0.001
Root throw	0.02 (> 0)	0.02 (2)	0	0
Debris flow	5.57 (65)	0.37 (42)	0	0
Total	8.55	0.88	1.4	0.054

Values in parentheses are percentages of the column total.

increase by one or two orders of magnitude as additional material is mobilized by processes like root throw and surface erosion each year. Even so, creep influences would remain dominant in terms of mass involved in movement (tab. 2).

Given the slow rate of creep movement (ca. 1 mm/yr) the importance of this process is greatly diminished when transport is expressed in terms of work. 65% of the annual geomorphic work in the basin is ascribed to debris flow activity, an indication of the significance of catastrophic processes in the development of the Cascade landscape. 25% of the work is due to dissolved material transport and only 10% to slow mass wasting (tab. 2). The two process sets (debris flow and solute transport) which account for 90% of geomorphic work in the basin both involve the removal of material from it. This suggests a correspondence of material output from Watershed 10 with the processes acting on its slopes. However, a scale dependence is implicit in this for debris flows deliver sediment to the fan at the basin mouth and so an equivalent correspondence of yield and slope activity would not be evident in larger catchments.

On the Martinelli site, there is no evidence of processes such as debris flows, though they are common elsewhere in the Colorado alpine belt (Caine 1976b). This leaves the creep and solifluction processes dominant in terms of both mass and work (tab. 2). This set includes about 60% of the geomorphic work done in the catchment each year, largely in seepage areas and wet sites around the lower margin of the snow accumulations. Solute transport accounts for a further 30% of the geomorphic work done in the basin, approximately the same proportion as in Watershed 10.

Although the proportion of work done by solute transport is about the same, the actual rate at Martinelli is less, by a factor of 5, than at Watershed 10. The contrast in activity (up to an order of magnitude) is evident in other processes also (tab. 2). The sole exception to this is slow mass wasting which performs almost twice as much work at the alpine site.

Tab. 2 also defines some basic differences in the behavior of the slope systems in the two areas. It supports the conclusion that the forest landscape of the Cascades is "disturbance dominated", involving episodic removal of previously accumulated debris with periodicities of centuries for headwater channels and perhaps millenia for bedrock hollows (Swanson et al. 1982). In contrast, the slope system of the Colorado alpine is dominated by the slow operation of quasi-continuous processes for periods which may extend uninterrupted through an entire interglacial (Caine 1986).

The contrast is not an artefact of the lack of debris flow activity in the Martinelly budget. If debris flow processes in the basin were estimated proportionately from the Green Lakes Valley (Caine 1986), i. e. as in Watershed 10, they would perform only 3% of the total geomorphic work. Even that would be an overestimate for the Martinelli basin contains no evidence of past debris flows. The presence of mid-Holocene paleosols in snow accumulation sites like this one (Burns 1980) also suggests a long period without debris removal.

Table 3 Mass delivery to stream channels.

	Watershed 10		Martinelli	
	Inorganic (T/yr)	Organic (T/yr)	Inorganic (T/yr)	Organic (T/yr)
Dissolved material	2.9 (27)	0.3 (21)	0.966 (72)	0.062 (92)
Surface erosion	0.53 (5)	0.3 (21)	0.37 (28)	0.005 (8)
Soil creep	1.1 (10)	0.04 (3)	0.001 (> 0)	0.0
Root throw	0.1 (1)	0.1 (7)	0.0	0.0
Debris flow	6.0 (57)	0.41 (28)	0.0	0.0
Litterfall	0.0	0.3 (21)	0.0	0.0
Total	10.63	1.45	1.33	0.067

Values in parentheses are percentage of the column total.

Channel supply

The supply of material to the channels of Waterhsed 10 and the Martinelli basin is summarised in tab. 3. These data represent material output from the hillslopes, unaffected by internal transfers within the slope system. Further transport along the channel is measured here as export from the basin and treated below. Channel lengths in the two basins are approximately equivalent (tab. 1), although the channels of Watershed 10 are larger than those of Martinelli, reflecting higher peak discharges and a fixed channel position.

For Watershed 10, the budget of inorganic materials in tab. 3, like that in tab. 2, is dominated by debris flows which account for 55% of the mass transported to the channel. Solutes also constitute a major (30%) component of the mass supplied to the stream channel. In contrast, surface erosion and soil creep processes are less significant, accounting for 5% and 10% of the total mass respectively. These proportions are all approximately the same as those ascribed to the same processes in evaluating geomorphic work on the basin slopes.

The relative contributions of sediment supplied to the Martinelli stream channels differ from those of Watershed 10 and from the proportions defined by work on the catchment slopes (tab. 3). They are dominated by the mass of dissolved material, about 70% of the total supply, while almost all of the rest is due to surface erosion adjacent to the stream channel (tab. 3).

The total volumes of inorganic sediment supplied to the stream channels of Watershed 10 is almost an order of magnitude greater than that in Martinelli (tab. 3), matching the pattern of slope activity. When the mass of organic material supplied to the channels is considered, between-basin differences are even greater (tab. 3).

However, it is surprising that the contrast is not more than a factor of 20, given a 60-fold difference in above-ground biomass (125 kg/m^2 in the H. J. Andrews Experimental Forest and 2 kg/m^2 on Niwot Ridge). Furthermore, the vegetation in the Martinelli basin is on its peripheries whereas that of Watershed 10 is so tall that litter falls directly into the channel. These differences are reflected in the proportion of dissolved organic material supplied to the channel: more than 90% at Martinelli and only 20% in Watershed 10.

Table 4 Mass yield from two mountains basins.

	Watershed 10		Martinelli	
	Inorganic (T/yr)	Organic (T/yr)	Inorganic (T/yr)	Organic (T/yr)
Dissolved material	2.9 (32)	0.3 (28)	0.956 (96)	0.062 (94)
Suspended sediment	0.78 (9)	0.12 (11)	0.039 (4)	0.004 (6)
Bed Load transport	0.6 (7)	0.33 (30)	0.002 (> 0)	0.0
Debris flows	4.6 (52)	0.33 (31)	0.0	0.0
Total	8.88	1.08	0.997	0.066

Values in parentheses are percentages of the column total.

Basin yields

Tab. 4 summarizes the yields of material from the two basins. They are of slightly lower than the estimates of supply, suggesting storage or use within the channel.

At Watershed 10 the budget of inorganic materials remains dominated by debris flow transport, though this dominance is reduced from that defined in tabs 2 and 3. Transport from the basin by debris flows, largely to the fan at its mouth, amounts to just over 50% of the total annual inorganic material export. Solute transport, at about 33%, remains equivalent to that delivered to the channel. This constant proportion is a procedural artefact for the within-basin exchanges are derived from export volumes on the assumption of negligible change along the channel (SWANSON et al. 1982). Fluvial transport of clastic sediment accounts for the remaining 15% of mass export, with slightly more suspended load than bedload (tab. 4).

At Martinelli, there is a clear dominance by solute export of inorganics, 95% of the annual yield (tab. 4). Even adding a debris flow estimate (as above) would only reduce this to 90%. So, the general pattern in the Martinelli basin remains that of low sediment yields throughout. The sediment is predominantly fine silt and clay with little material coarser than 32μ being removed by streamflow from the basin. Thus, the channel behaves as a filter, passing the silt and clay supplied to it (after a one year lag) and retaining sand and gravel (fig. 2). This is in accordance with the texture of alpine lake sediments in the Colorado Front Range (CAINE 1986).

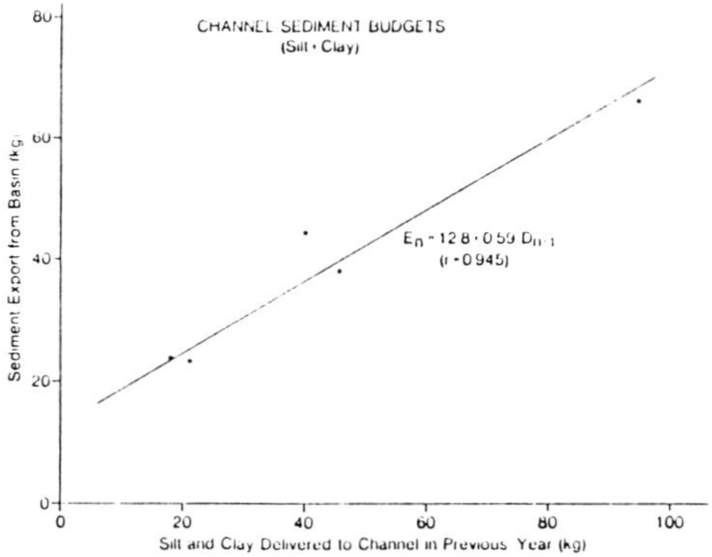

Fig. 2. Annual budgets of silt and clay for the Martinelli stream system. The empirical relationship suggests a lag of 1 year between silt-clay delivery to the channel and its removal from the basin.

The contrast between the two catchments with regard to inorganic yields repeats that found higher up the flow path. Exports from the Martinelli basin are an order of magnitude lower than those from Watershed 10. Considering only the particulates would increase the difference to more than two orders of magnitude.

This contrast is less marked with respect to the total mass of organic materials (tab. 4). Organic yields from both basins are close to those of supply to their respective channels and the proportionate difference between the two yields is equivalent to that in supply (tab. 3). Thus, both catchments have organic exports adjusted to supply, despite a twenty-fold difference in the total mass transported and a large difference in the relative proportions of particulate and dissolved organics. These data also suggest that, in such small basins, much more organic material is removed by transport through the channels than by oxidation and respiration (TRISKA et al. 1984).

Discussion

The behavior of these two catchments differs in three respects: (1) in level of activity; (2) in relative rates of hillslope and channel development; and (3) in the correspondence of mass flux at different points along the flow paths. These contrasts have implications for long-term landscape development.

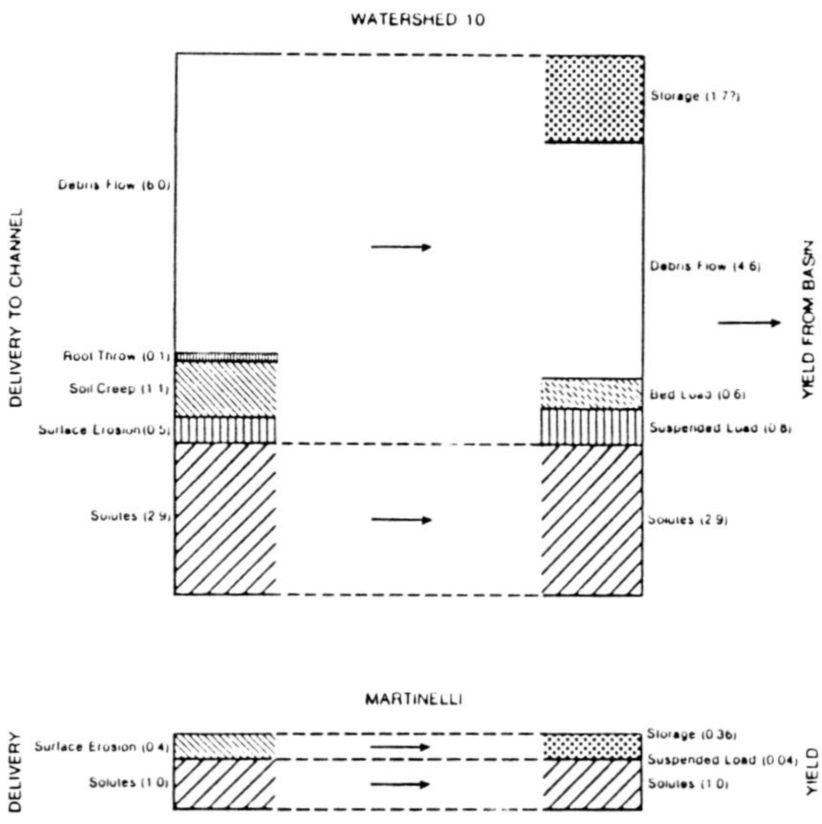

Fig. 3. Sediment budgets of two mountain basins. A: Watershed 10, H. J. Andrews Experimental Forest. B: Martinelli Catchment, Niwot Ridge.

Watershed 10 has annual rates of inorganic transfer that are an order of magnitude greater than those at Martinelli (fig. 3). Including organic materials in the comparison increase the contrast by a factor of two. The greater level of activity in Watershed 10 is associated with a doubling of annual precipitation (including a 10× increase in the amount of precipitation that falls as rain), a fivefold contrast in biomass, and a weaker bedrock. It is also associated with a marked contrast in basin form. Watershed 10 consists of landforms produced by processes equivalent to those acting in it today; the Martinelli basin is a relict form with inefficient coupling of present geomorphic processes.

The most marked contrast in geomorphic activity in the two basins involves the significance of catastrophic processes. Activity in Watershed 10 is dominated by slope failure and debris flows with a recurrence interval of ca. 400 years (SWANSON et al. 1982). This gives a high variabilty to annual (and even decadal and century-scale) measures of geomorphic acticity, but an approximate steady state in terms of sediment fluxes on the time scale of millenia. In contrast, the Martinelli system is dominated by more continuously-acting processes and is less variable on the same time scale. This seems to have been true for at least the last 5000 yr. Changing the behavior of this system requires a much longer time scale and the intervention of glacial conditions (CAINE 1986). Thus, the resetting mechanism in Watershed 10 is an internal one associated with the crossing of intrinsic threshold (SCHUMM 1979) of slope stability during storms while that in the Martinelli basin depends on external events initiated by global climatic change. In the first, the triggering event has a duration of hours or days; in the second, one of years or centuries.

On the time scale of centuries, the geomorphic system of Watershed 10 shows an approximate balance of material delivery and export with a ratio of yield to channel delivery of about 0.80 (tab. 5). Although the budget for a single year is

Table 5 Sediment delivery ratios for two mountains basins.

	Including Dissolved Material		Excluding Dissolved Material	
	WS-10	Mart.	WS-10	Mart.
Export/Slope				
Inorg.	3.3×10^{-5}	1.6×10^{-5}	2.2×10^{-5}	6.5×10^{-7}
Organic	8.0×10^{-5}	13.0×10^{-5}	6.0×10^{-5}	8.0×10^{-6}
Export/Delivery				
Inorg.	0.835	0.75	0.774	0.110
Organic	0.720	0.943	0.650	0.800
Delivery/Slope				
Inorg.	4×10^{-5}	2.1×10^{-5}	3.0×10^{-5}	6.0×10^{-6}
Organic	12.0×10^{-5}	13.0×10^{-5}	9.0×10^{-5}	1.0×10^{-5}

Ratios are defined by:
Export: mass exported from the basin through the channel
Deliver: mass transferred to the the channel
Slope: mass mobilized by transport on the channel

unlikely to balance the absence from the basin of landforms, deposits, paleosols, and other features indicative of net aggradation supports such a conclusion. Over a longer time, the budget should show a deficit, to accomodate channel lowering.

Despite lower levels of activity, the Martinelli basin shows a similar approximate balance (ratio of 0.76) between material supply to the channel and export through it (tab. 5). However, this is a spurious balance for it is dominated by solute transport, assumed constant along the channel. When particulate sediment alone is considered, only about 10% of the inorganic supply to the channel is removed from the basin (tab. 5). 90% remains within the aggrading channels of the basin floor, a process which has continued for centuries. This conclusion is supported by channel surveys that suggest aggradation rates of 0.21 m^3/yr, effectively identical to the 0.22 m^3/yr of sediment appearing as an excess in the sediment budget for the interval between surveys. Further, mid-Holocene paleosols in hollows like the Martinelli site (BURNS 1980) suggest that this aggradation has continued for millenia.

In contrast to the difference in the budgets of inorganic sediments, both basins show a close correspondence between organic material supply to the channel and export through it (tab. 5). This is about equivalent to that estimated by TRISKA et al. (1984) for nitrogen in Watershed 10. On the other hand, low productivity in the Martinelli basin means that organic material fluxes in it are an order of magnitude lower than those in Watershed 10.

These results have broad relevance to questions of landscape development. Obviously, extrapolating from an empirical record of decades or less to the time scale required for hillslope and drainage basin development is risky. However, some speculation is worthwhile because the contrast in catchment behavior is so great and may correspond to contrasting modes of landscape development.

A near-balanced sediment budget for Watershed 10 suggests that landscape development there is in a quasi-steady state. Over the long term, this should lead to the maintenance of both the channel system and the hillslopes above it in approximately the form of today, i. e. corresponding to the "equilibrium model" of THORNES & BRUNSDEN (1977: 118). This is achieved by irregular cycles of sediment accumulation and evacuation by debris flows (DIETRICH et al. 1986).

In contrast, the channels and riparian zone of the Martinelli catchment are an aggrading system. Rather than being maintained, the relief of the catchment should become more subdued through time. This corresponds to a "decay model" (THORNES & BRUNSDEN 1977; 119), involving progressive change that will only be interrupted by the "climatic accident" of renewed glacial conditions. It also contradicts the frequently-stated view that "nivation hollows", like the Martinelli basin, are associated with high rates of sediment removal (THORN 1988). Research at Martinelli suggests that the redistribution of clastic sediment within the basin dominates and that solute removal is the only effective mechanism of material export from it.

Conclusion

The contrasts in the long term and short term behavior of these two second-order mountain catchments are related to contrasts in geology, ecology, and history. In their present dynamics, both basins exhibit cyclic behavior. In Watershed 10, a cycle with a period of centuries, related to intrinsic thresholds in the basin, leads to the present landscape being maintained as an "equilibrium" form. In the Martinelli basin, the cycle is more speculative, with a period of 10,000 years or more and is driven by the extrinsic conditions of global climate. Over shorter intervals, the catchment landscape develops along a path of progressive relief reduction, but at a very slow rate.

Despite marked contrasts in the ecology, standing crop, and productivity of their catchments, both of these stream systems show a rough correspondence between the mass of organic material supplied to them and that transmitted out of them. In that respect, they act as relatively simple conduits of organic material, running from high ground to the large aquatic systems at lower elevations.

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References

BENEDICT, J. B. (1970): Downslope soil movement in a Colorado alpine region; rates, processes, and climatic significance. – Arct. & Alp. Res. 2: 165–226.

BHOWMIK, N. G. (1987): Hydrologic research at LTER sites. – Eos 68: 745, 750, 756.

BORMANN, F. H. & G. E. LIKENS (1967): Nutrient cycling. – Science 155: 424–429.

BURNS, S. F. (1980): Alpine Soil Distribution and Development, Indian Peaks, Colorado Front Range. – Ph.D. thesis, Dep. Geol. Sci., Univ. Colorado, Boulder; 360 pp.

CAINE, N. (1976a): Summer rainstorms in an alpine environment and their influence on soil erosion, San Juan Mountains, Colorado. – Arct. Alp. Res. 8: 183–196.

– (1976b): A uniform measure of subaerial erosion. – Geol. Soc. America, Bull. 87: 137–140.

– (1986): Sediment movement and storage alpine slopes in the Colorado Rocky Mountains. – [In:] ABRAHAMS, A. D. (ed.): Hillslope Processes: 115–137. Allen & Unwin, London.

CALLAHAN, J. T. (1985): Long-term ecological research: a national perspective. – Paper presented at Spec. Conf., Hydraul. Div., A.S.C.E., Lake Buena Vista, Florida, Aug. 12–17, 1985.

CUMMINS, K. W., J. R. SEDELL, F. J. SWANSON, G. W. MINSHALL, S. G. FISHER, C. E. CUSHING, R. C. PETERSON & R. L. VANNOTE (1983): Organic matter budgets for stream ecosystems: problems in their evaluation. – [In:] BARNES, J. R. & G. W. MINSHALL (eds): Stream Ecology: Application and Testing of General Ecological Theory: 299–353. Plenum Press, New York.

DIETRICH, W. E., C. J. WILSON & S. L. RENEAU (1986): Hollows, colluvium and landslides in soil-mantled landscaped. – [In:] ABRAHAMS, A. D. (ed.): Hillslope Processes: 361–388. Allen & Unwin, London.

SCHUMM, S. A. (1977): The Fluvial System. John Wiley & Sons, New York; 338 pp.

– (1979): Geomorphic thresholds: the concept and its application. – Inst. Brit. Geogr. Trans. 4: 485–515.

STRAHLER, A. N. (1957): Quantitative analysis of watershed geomorphology. – Amer. Geophys. Union Trans. 38: [illegible]–920.

SWANSON, F. [illegible] J. [illegible] (1988): The Long-Term Ecological research Program. – Eos 69: 34, 36, 46[illegible]

SWA[illegible] R. [illegible] FREDRIKSEN & F. M. McCORISON (1982): Material transfer in a western Oregon fore[illegible] watershed. – [In:] Analysis of Coniferous Forest Ecosystems in the Western United States: [illegible] Stroudsburg, Pennsylvania, Hutchinson Ross Publ. Comp.

[illegible] (1988): Nivation: a geomorphic [illegible] [In:] CLARK, M. J. (ed.): Advances in Periglacial Geomorpholog[illegible] Chichester.

[illegible] morphology and Time. Methuen, London; 208 pp.

[illegible] budget studies: can we assume stream steady state? – Science 188: [illegible]

[illegible] J., J. R. SEDELL, K. CROMACK Jr, S.V. GREGORY & F. M. McCORISON (1984): Nitrogen budget for a small coniferous forest stream. – Ecol. Monogr. 54: 119–140.

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