Geo-Eco-Trop, 1978, 1, 113-129

SEDIMENT YIELD IN UNGLACIERISED ALPINE AND TROPICAL LOW TO MODERATE RELIEF RAINFOREST ENVIRONMENTS

by

O. Slaymaker *

RESUME

Malgré les difficultés dues au manque d'homogénéité des mesures de la teneur en sédiment des rivières (échelle des bassins, période des observations), l'auteur compare la dégradation spécifique de deux environnements assez différents : le milieu alpin sans glacier et le milieu forestier tropical de basse altitude.

Les mesures qui ont été réalisées récemment montrent que les valeurs avancées antérieurement ont été exagérées : pour chacun des environnements, 20 B en moyenne, 40 B au maximum et non 80, voire 1000 B (1 B = 1 Bubnov = 1 m^3 $km^{-2}an^{-1}$). Les quantités transportées en suspension et en solution semblent être à peu près égales dans les deux milieux.

Dans les deux environnements, également efficaces du point de vue géomorphologique, les phases climatiques antérieures ont encore une influence restreinte mais non négligeable. En effet, elles ont abandonné des dépôts qui fournissent aujourd'hui aux rivières un matériel vulnérable dans les berges et le fond du lit. Le manteau d'altération profond sous la forêt intertropicale doit être, de même, considéré comme l'héritage d'une longue action de l'altération chimique.

L'importance de l'échelle du bassin a pu être mise en valeur uniquement dans le milieu alpin. Les petits bassins donnent les plus faibles teneurs, les bassins moyens les plus élevées. Ce principe n'a pu être vérifié dans les régions intertropicales.

The inherent variability of sediment yield data and the lack of an agreed spatial and temporal scale within which to make comparisons has hampered attempts to demonstrate regional variations in sediment yield (HOLEMAN, 1968 ; MENARD, 1961 ; FOURNIER, 1969 ; WILSON, 1973 ; JANSEN and PAINTER, 1974). The variance of the data and the scale problem have also inhibited the use of sediment yield data as indices of denudational activity in different environments (CORBEL, 1959, 1964 ; FOURNIER, 1960). Other caveats have been expressed by MEADE (1969), STODDART

---

* Department of Geography, University of British Columbia, VANCOUVER 8, B.C., Canada.

(1969) and JANDA (1971). A recent summary by YOUNG (1974) gives an overview of sediment yield data from a variety of morphoclimatic zones and CAINE (1974) and DOUGLAS (1969) have discussed sediment yield in alpine and tropical rainforest environments respectively. RAPP (1974) has made an interesting comparison of slope erosion in tropical and arctic mountains.

This paper attempts to define two zones within which the climatic and sediment yield variance is greatly reduced by comparison with standard morphoclimatic zones as defined by TRICART and CAILLEUX (1965), The zones are nevertheless of significant areal extent at a G-scale of 1.5 to 2.5 (HAGGETT et al, 1965). The unglacierised alpine zone is defined as a subdivision of the "mountains in which vertical zonation is important" (TRICART and CAILLEUX, 1965). The mean annual temperature is - 15° to 0° C, mean annual precipitation is greater than 150 mm and glaciers are absent. The final criterion is introduced because any attempt to evaluate mean denudation rates for glacierised basins from sediment movement data is completely spurious. Temporal and spatial variability is too great (SLAYMAKER 1974 a, 1974 b). An estimated 2×10^6 km^2 of the earth's surface are occupied by this zone.

The low to medium relief tropical rainforest zone is defined as a subdivision of the "tropical forests" (TRICART and CAILLEUX, 1965). The mean annual temperature is 20–30° C, mean annual precipitation is greater than 1500 mm and high relief areas such as Assam and New Guinea are excluded. This final criterion is introduced because published evidence (RUXTON and McDOUGALL, 1967 ; SIMONETT, 1967 ; STARKEL, 1972 ; PAIN and BOWLER, 1973) shows that in high relief tropical forests, the effect of relief dominates that of climate. An estimated 12×10^6 km^2 of the earth's surface are occupied by this zone.

Two reasons are suggested for making this comparative study. Firstly, the two environments are very different in terms of vegetation cover, relief, surface morphology and active climatic processes. Secondly, and more tentatively, the two environments have comparatively well understood Quaternary histories such that, in principle, it should be possible to relate the effects of climate to sediment yield without major complications from inherited deposits and forms from past different climates (BUDEL, 1959). In the case of the tropical rainforest, it is held by many (e.g. TRICART and CAILLEUX, 1965) that the climate has remained quite stable throughout Quaternary time ; or at least that continuous forest cover has been maintained in spite of temperature and precipitation changes. The implication would be that sediment yield has remained rather constant over the same time period. For unglacierised alpine environments, the Quaternary climatic perturbations were so extreme that all evidences of earlier climatic regimes were destroyed and sediment yield can be conceived as the result of present climate operating on initial bedrock or thinly regolith covered surfaces.

The role of tectonic activity, which is unquestionably an important factor in sediment yield studies (STODDART, 1969 ; DOUGLAS, 1969) is not explicitly investigated in this paper.

SEDIMENT YIELD DATA

The sediment yield unit which is now commonly accepted is that of the Bubnov (FISCHER, 1969), hereafter referred to as B. 1 B is equivalent to 1 m^3 km^{-2} yr^{-1} or 1 mm of ground loss per 1000 yr. If the mean specific gravity of the rocks at the earth's continental surface is 2.65 than 1 B is also equivalent to 2.65 metric tons km^{-2} yr^{-1} or 7.69 English short tons mi^{-2} yr^{-1}.

a) Tropical rainforests of low to medium relief.

Early estimates of sediment yield from this environment ranged from CORBEL (1964) who quoted 15-30 B, through STRAKHOV (1967) who estimated 40-80 B. to FOURNIER (1960) who showed a range from 45-1000 B, excluding dissolved load. More recently, DOUGLAS (1969) has shown that these are overestimates of the actual rates of sediment yield in tropical rainforests. Table 1, which uses data from ROUGERIE (1962), DOUGLAS (1973), GIBBS (1967) and SPRONCK (1941), confirms Douglas' contention and is itself thought to be an overestimate because some of the rivers rise outside the tropical rainforest zone. BREMER (1973) has provided geomorphic evidence from Amazonia which supports the suggestion of low rates of contemporary denudation and THOMAS (1974) reviews the available evidence from geomorphic, hydrologic and pedologic work.

Although no great significance is attached to the absolute values in this table, it is thought that they represent an upper limit for sediment yield from tropical rainforests of moderate relief under relatively undisturbed conditions. The more surprising result is the similar order of magnitude of dissolved sediment yield as compared with suspended sediment yield (cf. ALEKIN and BRAZNIKHOVA, 1968 ; DURUM at al, 1960). Solution is commonly thought to be the dominant process in tropical rainforests (e.g. BIROT, 1960) but few of the data quoted here support such a hypothesis.

The major conclusion is that sediment yield for tropical rainforests of moderate relief is in all cases less than 40 B, and averages less than half this value.

Table 1 Sediment yield data from the tropical rainforest (low to moderate relief) zone

River Basin	Basin Area (km^2)	Suspended Sediment (B)	Dissolved Sediment (B)	Sediment Yield (B)
Barron[1]	12	5.6	8.4	14.0
Davies	14	2.0	4.3	6.3
Millstream	20	6.2	7.2	13.4
Freshwater	44	5.5	4.0	9.5
Me[2]	4000	6.0	14.0	20.0
Agneby	8700	2.0	7.0	9.0
Tefe[3]	24,400	0.9	4.7	5.6
Araguari	45,200	2.8	6.2	9.0
Coari	55,500	0.8	5.0	5.8
Jutai	74,000	15.0	1.9	16.9
Javari	106,000	26.0	4.3	30.3
Jurun	217,000	19.0	12.5	31.5
Puruo	372,000	17.0	11.5	28.5
Tapajos	500,000	0.5	1.4	1.9
Xingu	540,000	0.3	1.0	1.3
Negro	755,000	3.8	3.7	7.5
Zaire[4]	3,700,000	3.6	11.2	14.8

[1] Douglas, 1973

[2] Rougerie, 1962

[3] Gibbs, 1967

[4] Spronck, 1941

Table 2 Sediment yield data from unglacierised alpine zone

River Basin	Basin Area (km^2)	Suspended Sediment (B)	Dissolved Sediment (B)	Sediment Yield (B)
Central Creek [1]	2.4	< 2	5	< 7
Sage Hen Creek [2]	2.74	–	1.4-1.9	–
Jamieson Creek [3]	3.0	–	5.3	–
Marmot Creek [4]	9.0	2.0	Carbonates	–
3 Sangre de Cristo Creeks [5]	15.0-90.0		3.0	
Kärkevagge [6]	15.0	5.5	10.4	15.9
Abisko	–	3.0	12.0	15.0
Little Sandy Creek [7]	54.0	–	2.1	–
Highwood [8]	133.0	4.9	Carbonates	–
Cataract	162.0	9.9	Carbonates	–
Whirlpool	687.0	25.8	Carbonates	–

1. Slaymaker, unpublished
2. Marchand, 1971 (Suspended sediment yield over last 10.9 million years estimated at 20B, but contemporary rate not determined.)
3. Zeman, 1975.
4. Slaymaker, 1972
5. Miller, 1961
6. Rapp., 1960
7. Hembree and Rainwater, 1961.
8. McPherson, 1975.

b) Unglacierised alpine environments

Early estimates of sediment yield from this environment range from STRAKHOV (1967) who estimated 20-> 100 B, through FOURNIER (1960), who showed a range from 45-1000 B, to CORBEL (1964) from 92-385 B. YOUNG (1974) summarises the best available evidence to give 92-750 B with an average of the order of 500 B. CAINE (1974) notes the curious inconsistency between sediment yield data and field measurements of the rate of operation of individual processes, but does not attempt to rationalise it. Table 2, which uses data from RAPP (1960), MARCHAND (1971), SLAYMAKER (1972), McPHERSON (1975), ZEMAN (1975), HEMBREE and RAINWATER (1961) and MILLER (1961) suggests that conventional wisdom has tended to exaggerate sediment yield in alpine zones even more than in the tropical forest zone. It seems probable that 40 B is an upper limit for sediment yield in this zone, and that 10-20 B is more typical in non-carbonate lithologies. Even in non-carbonate lithologies it seems that dissolved sediment yield is at least as important as the suspended sediment yield (cf. RAPP, 1960).

Inspection of data for one basin, in British Columbia, which incorporates substantial alpine zone, suggests reasons why earlier estimates have been so overestimated.

Table 3 Sediment yield data from Fraser River Basin

Basin	Basin Area (km^2)	Suspended Sediment (B)	Dissolved Sediment (B)	Sediment Yield (B)
Central	2.4	<2	0.5	7
Miller	21.	13.0	7.8	20.8
Lillooet	3,800			
(a) Pre-land use changes		137	–	–
(b) Post-land use changes		414	73	487
Fraser	200,000	43	–	–

Evidently, sediment yield reaches a maximum at some intermediate scale, where sediment availability to the channel is high because of extensive glacial depositional materials (FLEMING and POODLE, 1970). At this scale too it appears that land use changes become of major significance as the basin incorporates increasing proportions of sub-alpine and non-alpine terrain. It is possible that early high estimates of sediment yield in the alpine zone derive largely from stations located in these sub-alpine and non-alpine regions.

It is concluded that gross sediment yield data do not discriminate between unglacierised alpine and moderate relief tropical rainforest environments. Both show sediment yields averaging 10-20 B and, of this total, similar amounts are accounted for by solute load and suspended load in non-carbonate lithologies.

CONCEPTUAL FRAMEWORK FOR COMPARISON OF SEDIMENT AND SINKS YIELDS

It is important to try to clarify why two such different environments may have similar sediment and solute yields. Table 4 suggests a conceptual framework for the following discussion.

Table 4 Qualitative model of sediment and solute sources, sinks and yields

Source of sediment and solutes	Tropical Rainforest			Unglacierised Alpine		
	Sources	Sinks	Yield	Sources	Sinks	Yield
1. Atmosphere	***	***	**	***	***	**
2. Biosphere	****	****	**	***	***	**
3. Lithosphere						
a) surface erosion	***	****	*	****	***	****
b) subsurface erosion	****	**	****	****	**	****
c) bed and bank erosion	****	***	****	**	**	**

1. Asterisks indicate order of importance of sediment and solutes in each component of the model.

The numbers should not be interpreted as ordinal values, but they are rankings based on best estimates from the literature. It should be noted that rows 1, 2, and 3 b are primarily solute load and rows 3a and 3c are primarily clastic materials. It can be seen (a) that total yield in each zone may be similar and (b) that solute load and suspended sediment yield may be quite similar even if surface erosion is more important in unglacierised alpine zones and bed and bank erosion is more important in tropical rainforests.

With this crude framework in view, it may be possible to analyse each of a number of processes and indicate where differences in the sediment budgets of basins in tropical rainforest and unglacierised alpine environments occur. BIROT (1970) has discussed the problems of measurement associated with many of these processes.

ATMOSPHERIC SOLUTES

There are no a priori grounds for supposing that tropical rainforests are substantially different from unglacierised alpine environments as far as the supply and uptake of atmospheric solutes is concerned. There is an altitudinal effect which has been documented by, for example, MATVEYEV (1964), but proximity to maritime airmasses (ZEMAN, 1975), to industrial sources (ODEN and AHL, 1970), and volcanic emissions (JANDA, 1970) would likely be far more important. These latter factors woulds presumably influence tropical rainforests and unglacierised alpine environments in similar ways. Although there appears to be no preferred zonal yield from this source, and its absolute magnitude tends to be very small (row 1, table 4), it is important to recognise that, in any local study, stream solute load may be of similar order of magnitude and the partitioning of atmospheric, biospheric and lithospheric sources becomes a complex problem (ZEMAN and SLAYMAKER, 1975). On a zonal scale, the yield from this source is small.

BIOSPHERIC COMPONENTS

One of the two major observable differences between tropical rainforests and unglacierised alpine environments is the great amount of biologic activity in the former. But the weight of opinion suggests that this activity "is largely devoted to self regeneration, most of the nutrients falling to the forest floor being reused by the growing plants of the forest", (DOUGLAS, 1969). If this is indeed the case, then the yield of solutes may be of similar order of magnitude in these two dissimilar zones. "Most energy is used in the development of the plant community and not in erosion and removal of debris by streams", (DOUGLAS, 1969). By contrast the unglacierised alpine environment has the lowest level of biological productivity in the world, except for deserts and open oceans (WEBBER, 1974). It shows an average net primary productivity per unit area only one fifteenth as great as that of tropical rainforests. Again, the balance of opinion suggests that the alpine tundra ecosystem is a stable ecosystem, with only a very small net yield of solutes (BAZILEVICH and RODIN, 1971). On a zonal scale, the yield of solutes from the biosphere is small for both environments.

LITHOSPHERIC SOURCES

a) Chemical weathering and subsurface erosion

As most data pertaining to zonal chemical weathering derives from river water analyses, this is one of the more significant gaps in our knowledge. The simple model of CARSON and KIRKBY (1972) provides at least an index of zonal values where the rate of solution is proportional to (a) the saturated solubility of each oxide, (b) the quantity of the oxide present, and (c) the flow of water. The model predicts that highest rates of chemical weathering are found in areas of high precipitation, irrespective of whether they are hot or cold (based on findings of RAINWATER and GUY, 1961 ; KELLER and REESMAN, 1963 ; and LIVINGSTONE, 1963 a and b). For unglacierised alpine environments and tropical rainforests with more than 1500 mm of mean annual precipitation estimates of chemical weathering are given in table 5.

Table 5 Theoretical denudation by chemical weathering after Carson and Kirkby (1972)

	Igneous rock soil	Limestone
Tropical rainforest	5 B(1)	40 B
Unglacierised alpine	7 B	100 B

1. Calculations based on 1500 mm. mean annual precipitation.

Of course, alpine environments are frequently more arid, and tropical rainforests more humid, than 1500 mm. The CARSON and KIRKBY model shows a very good fit for the semi-arid alpine of the White Mountains of California (Table 6).

Table 6 Comparison between predicted and actual rates of chemical weathering for White Mountains, California.

	Area (km^2)	Lithology	Actual Chemical weathering B	Predicted Chemical weathering [2] B
Sage Hen Creek Basin [1]	2.74	94 % Adamellite	1.4-1.9	1- 2
Cottonwood Basin [1]	5.38	88 % Dolomite	17-21	10-20

1. Marchand, 1971.

2. Using model of Carson and Kirkby, 1972.

Preferential uptake by plants of iron, manganese and aluminum and probably potassium and phosphorus will provide a solute sink which reduces the absolute magnitude of solute yield in the streams. But the major components of weathered bed rock such as silica, calcium, magnesium and sodium are comparatively little affected.

b) Varieties of surface erosion

Some of the data are presented by YOUNG (1969, 1974) and CAINE (1974), in particular with respect to rates of cliff retreat. Values of 1000 B for alpine and up to 20,000 B for tropical rainforest are quoted but these are strictly relevant only to the rate of retreat of a specific free face. If these free face retreat rates are distributed over their respective basins the effective contribution to denudation is reduced by several orders of magnitude.

(i) Creep and solifluction

Few reliable data are available for tropical rainforests but those that are available are likely to be typical of whole basins. A measurement of 1 $cm^3.cm^{-1}.yr^{-1}$ can be converted to approximately 0.4 B if a drainage density of 2 $km.km^{-2}$ is assumed. In alpine environments, soil creep is commonly accelerated by the influence of freeze-thaw processes.

(ii) Rockfall and talus development

As these processes depend heavily on freeze-thaw effects (FRASER, 1959), there is a clear distinction between the zones. But, although these denudation rates are high, they apply only to the actual talus slopes measured. Zonally, the net contribution of these processes is probably less than 1 B even in alpine environments.

(iii) Debris slides and mudflows

These processes, which depend heavily on basal lubrication, appear to be more dominant in the humid tropics (RAPP, 1974). The reported data from Kirghizia (IVERONOVA, 1969) are site specific and would be much lower on a zonal scale. GARDNER (1970) and BROSCOE and THOMPSON (1969) give useful data on avalanches and mudflows as geomorphic agents in unglacierised alpine zones.

(iv) Surface wash

These data assume comparable infiltration capacities over whole basin areas and can be interpreted as integrated basin denudation rates. HUDSON (1961) and DE PLOEY (1969) discuss the role of intense precipitation in generating surface wash in tropical environments.

Table 7 - Contribution of various forms of surface erosion to denudation

Process	Tropical Rainforests		Unglacierised Alpine	
(a) Soil creep and solifluction*	Malaysia[1]	4-6B	Lappland[3]	2-10 B
	Puerto Rico[2]	2-5B	French Alps[4]	< 24 B
			British Columbia[5]	10-12 B
			Spitzbergen[6]	< 20 B
(b) Rockfall	N/A		Yukon[7]	8.8-44.36 B
(c) Debris slides and mudflows	only high relief and / or tectonically disturbed basin data available		Coast Mountains[8]	up to 30 B
			Kirghizia[9]	109 B
(d) Surface wash	Malaysia[10]	< 1B	Rockies[11]	5 B

* Data from published sources, converted to Bubnovs by comparing basins of identical drainage density (2 km.km^{-2}).

1. Eyles and Ho (1970)
2. Lewis, L.A., quoted in Young (1974)
3. Rudberg (1964, 1970)
4. Pissart (1964)
5. Slaymaker (1974b)
6. Jahn (1961)
7. Gray (1972)
8. O'Loughlin (1972)
9. Iveronova (1969)
10. Young (1974)
11. Dingwall (1972)

c) Bed and Bank erosion.

No specific data are available for these processes but upper limits are provided by the suspended sediment yield data.

Table 8 - Contribution of bed and bank erosion to denudation

Tropical Rainforest		Unglacierised Alpine	
Amazonia[1]	0.3 - 26 B	Green Lakes[2]	0.05 B
		Marmot Creek[3]	< 2 B
		Central Creek[4]	< 2 B

1. Gibbs (1967)
2. Caine (1974)
3. Slaymaker (1972)
4. Slaymaker (Unpublished)

CONCLUSIONS

(a) Rates of sediment yield in tropical rainforest and unglacierised alpine environments have been overestimated in the past. Contemporary surface lowering rates in these two environments average 10-20 B. This means, inter al, that the disparity between denudation and orogenesis noted by SCHUMM (1963) is even greather than he suggested, as his conclusions were based on a denudation rate for mountain summits of 900 B.

(b) Humid unglacierised alpine and tropical rainforest environments show comparable suspended sediment and solute yields. If sediment yield data for two such contrasted environments show no significant difference, their use as a quantitative tool in discriminating morphoclimatic zones should be discouraged.

(c) Attempts to predict sediment yield on a zonal basis are likely to be unsuccessful (for contrary position, see HERVIEU (1968) and JANSEN and PAINTER (1974).

(d) Unglacierised alpine environments show a scale effect whereby the smallest basins have lowest yields ; intermediate basins show highest yields and largest basins have intermediate yields (see JANDA, quoted in MARCHAND, 1971). For tropical rainforests, data are inadequate to confirm such a scale effect.

(e) Both environments show the effect of Pleistocene and recent history on sediment availability and hence on bed and bank erosion yields. In the case of the tropical rainforest environment, frequent changes of river course during the Pleistocene and Recent have increased sediment availability in some stream systems. In unglacierised alpine environments the distribution of glacial depositional materials from the Pleistocene influences sediment yield (cf. Whirlpool and Central Creeks).

(f) The tropical rainforests are particularly vulnerable to the impact of land use. Any land use change which alters the continuous vegetation cover generates a perturbation which is rapidly reflected in suspended sediment (surface erosion) yield and solute (biosphere) yield. Discussions of urban and agricultural land use impacts on tropical forest sediment yield can be found in Malaysian examples (DOUGLAS, 1968).

(g) Deep weathering profiles in tropical rainforests must be a result of length of time available under similar climatic conditions rather than rate of weathering.

(f) Measurable differences in rates of operation of individual processes which also give contemporary yield contrasts can be identified in (i) creep, solifluction, rockfall and surface wash, which are greater in unglacierised alpine environments, and (ii) debris slides and mudflows, which are probably greater in tropical rainforests.

REFERENCES

ALEKIN, O.A. and BRAZNIKHOVA, L.B. (1968) - The discharge of dissolved matter and chemical and mechanical erosion. *Pubs. Assoc. Intern. Hydrol. Scient.*, n^{o} 78, pp. 35-41.

BAZILEVICH, N.I. and RODIN, L.Y. (1971) - Geographical regularities in productivity and circulation of chemical elements in the earth's main vegetation types, *Soviet Geography*, v. 12, pp. 24-53.

BIROT, P. (1960) - Le cycle d'érosion sous les différents climats. University of Brazil, Rio de Janeiro, 137 p.

BIROT, P. (1970) - Etude quantitative des processus érosifs agissant sur les versants, *Zeits. für Geomorph., Supp. Band.* 9, pp. 10-43.

BREMER, H. (1973) - Der Formungsmechanismus in tropischen Regenwald Amazoniens, *Zeits. für Geomorph. Supp. Band.* 17, pp. 195-222.

BROSCOE, A. J. and S. THOMPSON (1969) - Observation on an alpine mudflow. Steele Creek, Yukon, *Can J. Earth. Sci.*, vol. 6, pp.219-229.

BUDEL, J. (1959) - Climatic zones of the Pleistocene. *International Geology Review*, vol. 1, pp. 72-79.

CAINE, N. (1974) - The geomorphic processes of the alpine environment, chapter 12 B in *Arctic and Alpine Environments* (Ives, J.D. and Barry, R.G. eds.) pp. 721-748.

CARSON, M.A. and KIRKBY, M.J. (1972) - *Hillslope Form and Process.* Cambridge University, 475 pp.

CORBEL, J. (1959) - Vitesse de l'érosion *Zeits. für Geomorph.* v. 3, pp. 1-28.

CORBEL, J. (1964) - L'érosion terrestre, étude quantitative *Ann. Geogr.* v. 73, pp. 385-412

DINGWALL, P.R. (1972) - Erosion by overland flow on an alpine debris slope. Chapter 3-5 in *Mountain Geomorphology* (Slaymaker, H.O. and McPherson, H.J. eds), pp. 113-120.

DOUGLAS, I. (1967) - Erosion of granite terrains under tropical rainforest in Australia, Malaysia and Singapore, *Pubs. Assoc. Intern. Hydrol. Scient.*, n^{o} 74, pp. 31-39.

DOUGLAS, I. (1969) - The efficiency of humid tropical denudation systems. *Trans. Inst. Brit. Geog.*, n^{o} 46, pp. 1-16.

DOUGLAS, I. (1973) - Rates of denudation in selected small catchments in eastern Australia. University of Hull. Occ. Papers in Geog., n^{o} 21, 127 pp.

DURUM. W.H. ; HEIDEL, S.G. and TISON, L.J. (1960) - World-wide runoff of dissolved solids. *Pubs. Assoc. Intern. Hydrol. Scient.* n^{o} 51, pp. 618-628.

EYLES, R.J and HO, R. (1970) - Soil creep on a humid tropical slope *J. Trop. Geogr.*, v. 31., pp. 40-42.

FISCHER, A.G. (1969) - Geological time-distance rates - the Bubnoff unit. *Bull. Geol. Soc. Am.*, v. 80, pp. 549-552.

FLEMING, G. and POODLE, T. (1970) - Particle size of river sediments, *Am. Soc. Civ. Eng., Hydr. Div. J.*, v. 96, pp. 431-439.

FOURNIER, F. (1960) - Climat et Erosion. Presses Universitaires de France, Paris, 210 pp.

FOURNIER, F. (1969) - Transports solides effectués par les cours d'eau. *Bull. Intern. Assoc. Scient. Hydrol.*, v. 14, pp. 7-49.

FRASER, J.K. (1959) - Freeze-thaw frequencies and mechanical weathering in Canada. *Arctic*, v. 12, pp. 40-53.

GARDNER, J. (1970) - Geomorphic significance of avalanches in the Lake Louise area. *Artic and Alpine Research*, v. 2, pp. 135-144

GIBBS, R.J. (1967) - The geochemistry of the Amazon River System : Part 1. The factors that control de salinity and the composition and concentration of the suspended solids. *Bull. Geol. Soc. Am.*, v. 78, pp. 1203-1232.

GRAY, J.T. (1972) - Debris accretion on talus slopes in the central Yukon territory, Chapter 3-1 in *Mountain Geomorphology* Slaymaker, H.O. and McPherson, H. J. eds) pp. 75-84.

HAGGETT, P. , CHORLEY, R.J. and STODDART, D.R. (1965) - Scale standards in geographical research : a new measure of areal magnitude *Nature*, v. 205, pp. 844-847.

HEMBREE, J.H. and RAINWATER, F.H. (1961) - Chemical degradation, Wind River Range, Wyoming *U.S. geol. Surv. Water Supply paper* 1535-E, 9 pp.

HERVIEU, J. (1968) - Contribution à l'étude de l'alluvionnement en milieu tropical. *Mémoires ORSTOM*, n^{o} 24, 465 p.

HOLEMAN, J.N. (1968) - The sediment yield of the major rivers of the world, *Water Ressources Research*, vol. 4, pp. 737-747.

HUDSON, N.W. (1961) - An introduction to the mechanics of soil erosion under conditions of sub-tropical rainfall, *Proc. Trans. Rhodesia Scient. Assoc.*, vol. 49, pp. 15-25.

IVERONOVA, M.I. (1969) - An attempt at the quantitative analysis of contemporary denudation processes, *Izv. Akad. Nauk. SSSR Ser. Geogr.*, pp. 13-24

JAHN, A. (1961) - Quantitative analysis of some periglacial processes in Spitzbergen, *Zesz. Nauk. Univ. Wroclaw*, Ser. B, 5, 56 p.

JANDA, R.J. (1971) - An evaluation of proceduresused in computing chemical denudation rates, *Bull. Geol. Soc. Am.*, vol. 82, pp. 67-80.

JANSEN, J.M.L. and PAINTER, R.B. (1974) - Predicting sediment yield from climate and topography, *J. Hydrol.*, vol. 21, pp. 371-380.

KELLER, W.O. and REESMAN, (1963) - Glacial milks and their laboratory simulated counterparts, *Bull. Geol. Soc. Amer.*, vol. 74, pp. 61-76.

LIVINGSTONE, D.A. (1963 a) - Chemical composition of rivers and lakes, *U.S. Geol. Surv. Prof. Paper 440-G.*

LIVINGSTONE, D.A. (1963 b) - Sodium cycle and the age of the ocean, *Geochim. et Cosmochim. Acta.*, vol. 27.

MARCHAND, D.E. (1971) - Rates and modes of denudation, White Mountains, eastern California, *Am. J. Sci.*, vol 270, pp. 109-135.

MATVEYEV, A.A. (1964) - Chemical composition of snow, ice and atmospheric precipitation in region of Elbrus glacierisation, *Gidrokhimichevkiye Materialv*, vol. 37., pp. 10-22.

McPHERSON, H.J. (1975) - Sediment yields from intermediate-sized stream basins in southern Alberta, *J. Hydrol.*, vol. 25, pp. 243-257.

MEADE, R.H. (1969) - Errors in using modern stream-load data to estimate natural rates of denudation, *Bull. Geol. Soc. Am.*, vol. 80, pp. 1265-1274.

MENARD, H.W. (1961) - Some rates of regional erosion, *J. Geol.*, vol. 69, pp. 154-161.

MILLER, J.P. (1961) - Solutes in small streams draining single rock types, Sangre de Cristo Range, New Mexico, *U.S. Geol. Surv. Water Supply Paper* 1533-F, 23 p.

ODEN, S. and AHL, T. (1970) - Försurningen av skandinaviska vatten *Särtryck ur Ymers Arsbok,* pp. 103-122.

O'LOUGHLIN, C.L. (1972) - A preliminary study of landslides in the Coast Mountains of British Columbia, chapter 3-4 in *Mountain Geomorphology* (Slaymaker, H.O. and McPerson, H.J. eds.), pp. 101-111.

PAIN, C.E. and BOWLER, J.M. (1973) - Denudation following the November, 1970 eartquake at Madang, Papua New Guinea *Zeits. für Geomorph., Supp. Band* 18, pp. 92-104.

PISSART. A. (1964) - Vitesses des mouvements du sol en Chambeyron (Basses Alpes) *Biul Peryglac.,* vol. 14, pp. 303-309.

DE PLOEY, J. (1969) - L'érosion pluviale : expériences à l'aide de sables traceurs et bilans morphogéniques. *Acta Geog. Lovaniensa,* vol. 7, pp. 1-28.

RAINWATER, E.H. and H.P. GUY (1961) - Some observations on the hydrochemistry and sedimentation of the Chamberlain Glacier area. *U.S. Geol. Survey Prof. Paper* 414-C.

RAPP, A. (1960) - Recent development of mountain slopes in Kärkevagge and surroundings, northern Scandinavia, *Geog. Ann.,* vol. 42, pp. 65-200.

RAPP, A. (1974) - Slope erosion due to extreme rainfall, with examples from tropical and arctic mountains in *Geomorphologische Prozesse und Prozesskombinationen in der Gegenwart* (Poser, H. ed.), pp. 118-136.

ROUGERIE, G. (1962) - Etude comparative de l'évacuation de la silice en milieux cristallins tropicaux humide et tempéré. *Ann. de Géog.,* vol. 70, pp. 45-50.

RUDGERG, S. (1964) - Slow mass movement processes and slope development in the Norra Storfjäll area, southern Swedish Lappland. *Zeits für Geomorph. Supp. Band 5,* pp. 192-203.

RUDBERG, S. (1970) - Recent quantitative work on slope processes in Scandinavia *Zeits, für Geomorph., Supp. Band. 9,* pp. 44-56.

RUXTON, B.R. and McDOUGALL, I. (1967) - Denudation rates in north-east Papua from potassium-argon dating of lavas. *Am. J. Sci.,* vol. 265, pp. 545-561.

SCHUMM, S.A. (1963) - The disparity between present rates of denudation and orogeny. *U.S. Geol. Surv. Prof. Paper* 454-H, 13 p.

SIMONETT, D.J. (1967) - Landslide distribution and earthquakes in the Bewani and Torricelli Mountains, New Guinea in *Landform Studies from Australia. and New Guinea* (Jennings, J.N. and Mabbutt, J.A. eds.) pp. 64-84.

SLAYMAKER, H.O. (1972) - Sediment yield and sediment control in the Canadian Cordillera, chapter 5-6 in *Mountain Geomorphology* (Slaymaker, H.O. and Mc Pherson, H.J. eds.) pp. 235-245.

SLAYMAKER, H.O. (1974 a) - Alpine hydrology, chapter 38 in *Arctic and Alpine Environments* (Ives, J.D. and Barry, R.G. eds.), pp. 133-158.

SLAYMAKER, H.O. (1974 b) - Rates of operation of geomorphological processes in the Canadian Cordillera in *Geomorphologische Prozesse und Prozesskombinationen in der Gegenwart* (Poser, H. ed.), pp. 319-332.

SPRONCK, R. (1941) - Mesures hydrographiques effectuées dans la région divagante du Bief Maritime du Fleuve Congo. *Mém. Inst. Roy. Colon. Belge,* Brussels, 156 p.

STODDART, D.R. (1969) - Climatic geomorphology : review and reassessment *Progress in Geog.,* vol. 1, pp. 159-222.

STRAKHOV, N.M. (1967) - Principles of Lithogenesis, vol. 1, Consultants Bureau, New York, 245 p.

THOMAS, M.F. (1974) - Tropical Geomorphology, Macmillan of Canada, Toronto, 320 p.

TRICART, J. and CAILLEUX, A. (1965) - Introduction à la Géomorphologie climatique, Paris, SEDES, 306 p.

WEBBER, P.J. (1974) - Tundra primary productivity, chapter 8 B in *Arctic and Alpine Environments* (Ives, J.D. and Barry, R.G. eds.), pp. 445-473.

WILSON, L. (1973) - Variations in mean annual sediment yield as a function of mean annual precipitation. *Am. J. Sci.*, vol. 273, pp. 335-349.

YOUNG, A. (1969) - Present rate of land erosion *Nature*, vol 224, pp 851-852.

YOUNG, A. (1974) - The rate of slope retreat, in *Progress in Geomorphology* (Brown, E. H. and Waters, R.S., eds.), pp. 65-78.

ZEMAN, L. I. (1975) - Hydrochemical balance of a British Columbia mountainous watershed. *Catena*, vol. 2, pp. 35-47.

ZEMAN. L. I. and SLAYMAKER, H.O. (1975) - Hydrochemical analysis to discriminate variable runoff source areas in a alpine basin *Arctic and Alpine Research*, vol. 7, n^{o} 4 (in press).

DISCUSSION

J. Savat : Do you think that bank erosion is an important factor to be taken into account in estimating the sediment yield of a basin ? If a bank is eroded at the left, deposits frequently happen at the right and this does not alter the balance of the downstream transported material significantly.

O. Slaymaker : At allbut the small watershed scale in alpine environments I believe that bank erosion is of primary significance as a contributor to sediment yield (see Caine, 1974). As far as humid tropical rainforests are concerned, I am not so sure, though Douglas provides data from Malaysia which would tend to confirm the importance of bank erosion. Sediment surveys in reservoirs usually show that slope processes are inadequate to account for accumulation rates (e.g. Kirkby, 1967 ; Slaymaker, 1972).

M.F. Thomas : Dr. Slaymaker's study poses a classical problem in geomorphology, namely that studies of actual erosion are sheldom able to confirm or refute the concepts of morphogenetic zonation. All morphogenetic zones (and therefore concepts) must include the inherited deposits and forms of past climates. If the conclusions of Dr. Slaymaker are accepted, that the main influences on rates of denudation are those of scale, Quaternary legacy and human land use then we should accept each study of actual denudation at the scale of enquiry and not attempt to construe the information within a morphogenetic framework on quite different scales of both space and time.

O. Slaymaker : I tried to make the point that the tropical rainforests could be expected to contain the fewest landform development complications from climatic change and that then therefore may give a climate-landform-sediment yield association which is rather direct. This suggestion should at least be explored before Dr. Thomas makes his negative conclusion.

L.K. Jeje : Dr. Slaymaker, you made some points on sediment yield and land use in humid tropical environments. Can you expatiate further on these points giving yields under specific land use type as this will help in the type of work I am trying to carry out on sediment yield and land use in Ife area ?

O. Slaymaker : The date I have quoted apply only to humid tropical rainforest environment. The published evidence (e.g. Holman, 1968) suggests that in the more seasonal humid tropics, such as the regions in which you work in Nigeria, the "natural" rates of sediment yield are much higher. I believe that any form of vegetation clearance in the humid tropical rainforest zone will raise the values of sediment yield above those which I have quoted, particularly at an intermediate or small watershed scale.

I. Douglas : Dr. Slaymaker was right to insist on the question of scale. The scale effects are both spatial and temporal. The lower portions of the slopes and valley floors act as storages for material brought down from higher upslope and higher upvalley. The release of this material to rivers is not controlled by the same hydrometeorological events as the detachment and movement of material on slopes. The delay between removal from slopes and entry into rivers may be only a few hours days or weeks in small basins, but thousands of years along the great rivers of the world.