Seasonal variation in the sediment delivery ratio of a forested drainage basin in Luxembourg.

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ABSTRACT The Schrondweilerbaach basin in Luxembourg is characterized by a sediment delivery ratio of near 100 percent. Sediment is delivered by a wide range of processes active on streambanks and valley slopes: bank scour, soil fall, creep, landslides, rainsplash erosion and overland flow. The combined effect of these processes reveals maximum supply rates during winter. In contrast sediment output, which mainly occurs as suspended load, is highest in summer. The phase difference between these major periods of sediment delivery and output induces wide seasonal variations in the sediment delivery ratio: about 25-50 percent in winter and 100-350 percent in summer. Moreover the results imply a distinct seasonal trend in sediment storage: net storage gain in winter and remobilization of winter stored sediment in summer. The close resemblance of annual delivery and output both of suspended and bed load is used to draw some conclusions on the geomorphic development of the basin.

KEYWORDS: sediment delivery ratio, sediment budget, channel storage, streambank erosion

INTRODUCTION

The sediment delivery ratio is defined as the percentage of the sediment delivered at a location on the stream system to the gross erosion on the basin (Robinson, 1977). In this view it is often used to compare regional differences in erosional/hydrological characteristics, to express sediment transport efficiency of the studied system or to develop sediment yield prediction equations for ungauged basins. The above definition clearly mentions the two composing factors: sediment yield and gross erosion (sediment delivery). While fairly accurate measurements and calculations of sediment yield are available, gross erosion is usually determined by applying a soil loss equation for the calculation of upland sheet erosion in combination with the estimation of additional contributions from gully and channel erosion (Piest et al., 1975; Renfro, 1975; Williams, 1977). Next to this approach some investigators estimate gross soil erosion from the degree of soil profile truncation (Trimble, 1975, Bork, 1983; van Hooff & Jungerius, 1984). However, as such estimates are open to considerable uncertainty more accurate sediment delivery ratios may only be obtained by detailed measurements of the various processes active in sediment delivery (Walling, 1983).

Moreover, ratios are generally computed on the basis of (long- of sediment storage and consequently would be a valuable completion to the study of sediment transfer.

In the present study both sediment delivery and sediment yield are measured on a monthly basis for a small forested basin in Luxembourg during the period 1979-1981. Attention is primarily paid to the seasonal variations in sediment supply by the various erosion processes, sediment output and the consequent sediment delivery ratios. Next to this the implications of varying in- and outputs of sediment on sediment storage are elucidated.

THE DRAINAGE BASIN

The investigations described here were made in the Schrondweilerbaach basin in the Grand-Duchy of Luxembourg. The upper, wooded part of the basin covers an area of 60.8 ha and has an altitude between 290 and 345 m. The bedrock consists of marls with interbedded sandstones and conglomerates. The weathering product of the marls (which underlie the largest part of the basin) has a clay (loam) texture and a highly aggregated structure, characteristic for Keuper marl (Dumbleton & West, 1967). Soils are poorly drained and shallow, leading to the development of a perched watertable above the subsoil. Soil characteristics of the basin and their implications for runoff generation, however, have been discussed elsewhere (Bonell et al., 1984; Duijsings, 1985). The forest in the drainage basin dominantly consists of oak, beech and hornbeam.

The gently to moderately sloping valley slopes (2-7°) have a microtopography of indistinct shallow depressions and ridges, the former being usually no more than 10-15 m wide. During wet weather runoff is generated from the depressions which become connected by poorly defined channels. Many of these drain into a system of narrow drainage ditches (dug in 1928) superimposed upon the original drainage network. The length of the stream channel system is 2250 m excluding the 1400 m of drainage ditches (Figure 1). Channel bed topography is rather irregular and is strongly dependent upon bed lithology and the presence of organic debris dams; in general, the channel bed gradient varies between 0.5° and 5.0°. Channel bank slope angles are between 40° and 55° while the depth and width of the incision vary respectively from 0.5 - 5.0 and 1.5 - 20 m.

Climatically the area is classified as humid temperate with rain in all seasons. The annual precipitation for the period under detailed investigations, Nov. 1979 - Nov. 1981, averaged 1050 mm. Runoff at the basin outlet averaged about 300 mm. The mean annual temperature is 9.1°C with about 80 days with below-zero temperatures.

APPROACH

The framework of this study is based upon a sediment budget approach in which sediment supply by the various erosion processes active on valley slopes and streambanks is measured and compared with sediment output from the basin.

Five processes were found to be active in streambank erosion: lateral corrasion (bank scour), bank failures, creep, rainsplash and subsoil fall (disintegration of subsoil into an incoherent mass of aggregates upon exposure to the atmosphere and subsequent transport of aggregates under the influence of gravity; Imeson & Jungerius, 1977). Programs to measure the sediment delivery by these processes were carried out at three sample areas comprising the variation in bank material characteristics and channel morphology. After the processes had been mesured for two years, multivariate relationships were established between the monthly amount of eroded material and a number of bank parameters (morphological variables

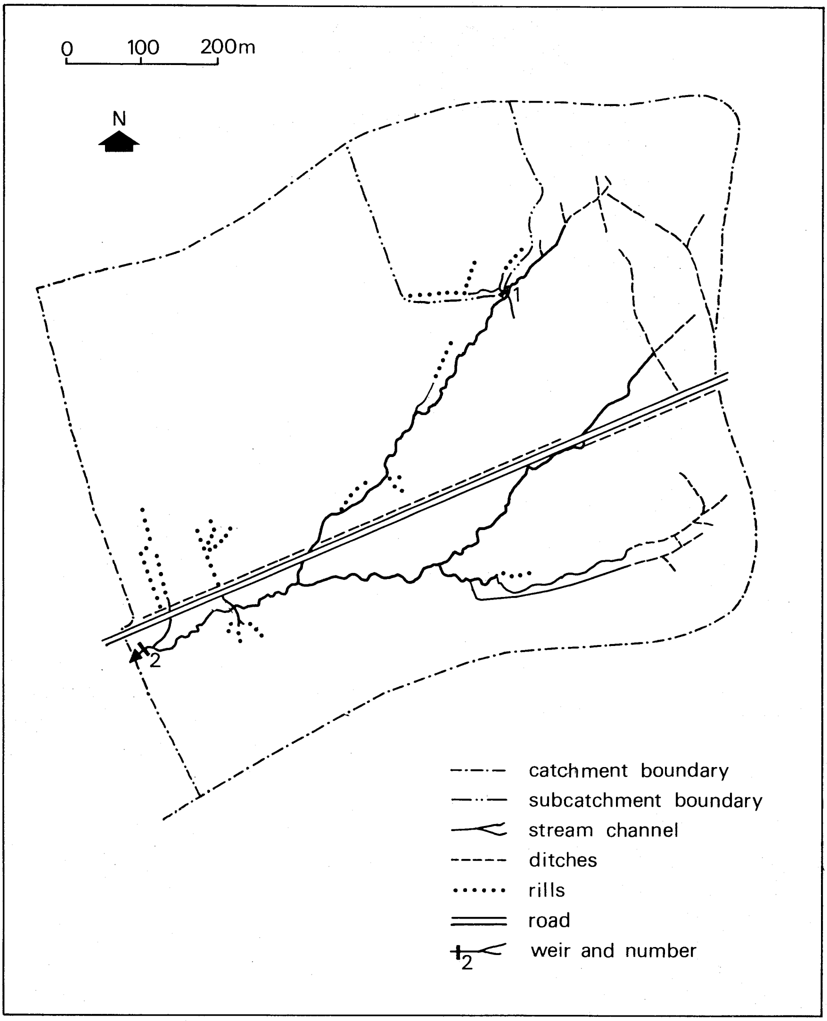

Figure 1 Drainage pattern of the Schrondweilerbaach basin.

and bank erodibility indices). In 1981 the channel was surveyed and the essential parameters were measured or determined along the entire channel reach. The relationships established for the sample areas were then used to calculate the total sediment supply by each of the bank processes.

Sediment transfer on the valley slopes was quantified both directly by measurements of rill and interrill erosion and indirectly by determining runoff and sediment discharge from a well-defined, representative subcatchment (Figure 1). Subsequently data were converted to the total basin area.

Sediment output from the Schrondweilerbaach basin was measured by continuously recording discharge and instantaneous measurements of suspended sediment concentration. Next to this total bed load yield during the study period was calculated from reservoir deposition.

More detailed information on the data collection methods have been

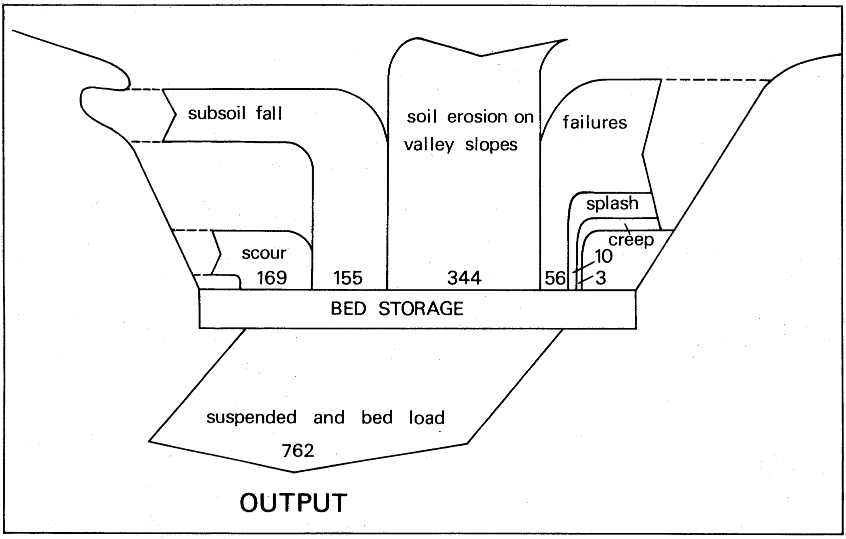

Figure 2 Sediment budget of the Schrondweilerbaach basin, 1979-1981. Numbers are in kg, ha^{-1}, yr^{-1}.

reported elsewhere (Duijsings, 1985, 1986). The results of the budget calculations are schematically represented in Figure 2 in which the various sediment source areas are indicated.

SEASONAL VARIATION IN SEDIMENT DELIVERY AND SEDIMENT OUTPUT

The monthly rates of sediment input to the streambed from the valley slopes and the individual streambank processes are given in Table 1 while their corresponding totals are shown in Figure 3 in connection with sediment output.

Supply from the streambanks is highest in winter resulting from the large degree to which the rates of subsoil fall and bank scour (the major bank processes, Figure 2) are related to frost intensity and duration (preparation of bank material; Duijsings, 1985) and magnitude of discharge. The highest value for bank scour supply, however, was recorded during July 1981 when a very intense thunderstorm with an estimated recurrence interval of about 50 years struck over the area. Sediment delivery by splash erosion shows distinct summer peaks as it is closely related to the erosivity of rainfall: summer throughfall appeared to be 1.65 times as erosive as winter throughfall due to the higher intensity of summer rainfall and the effects of the forest canopy on dropsize distribution and kinetic energy of throughfall (Mosley, 1982; Duijsings, 1985).

Soil creep is the least important process as it only contributes 0.8 percent of the sediment transfer from the banks. The sediment supply tends to be highest at end November/begin January related to the combined effects of biological activity in the topsoil and frost influences (Duijsings, 1985).

Splash detachment and subsequent transport of detached material by overland flow appeared to be the dominant mechanism of soil erosion on valley slopes. Both the rate of splash detachment and runoff generation are influenced to a large degree by the forest ecology; apart from the

Table 1 Monthly rates of sediment transfer (kg) by streambank processes, valley slopes and basin output

	STREAMBANKS					VALLEY SLOPES	OUTPUT
period	scour	soil fall	splash	creep	slides		*
25/10 - 16/11/79	0	324	19	25		700	1550
16/11 - 15/12/79	970	803	51	43		1060	3880
15/12 - 11/ 1/80	258	396	46	20		2060	2700
11/ 1 - 9/ 2/80	2269	1826	50	5	670	450	2380
9/ 2 - 9/ 3/80	0	326	39	6		210	160
9/ 3 - 11/ 4/80	0	296	23	18		1130	890
11/ 4 - 9/ 5/80	1671	926	33	45		2120	1875
9/ 5 - 30/ 5/80	0	108	24	8		40	75
30/ 5 - 3/ 7/80	825	475	90	0		2550	8440
3/ 7 - 3/ 8/80	309	869	88	6		850	3450
3/ 8 - 31/ 8/80	453	439	102	18	1250	1220	4750
31/ 8 - 29/ 9/80	0	58	19	23		0	100
29/ 9 - 25/10/80	52	81	45	12		25	760
25/10 - 22/11/80	670	628	15	10		670	1040
22/11 - 18/12/80	1362	1522	24	29	1400	3050	1975
18/12 - 16/ 1/81	743	1358	25	18		2850	2020
16/ 1 - 13/ 2/81	330	2376	37	4		2740	1370
13/ 2 - 12/ 3/81	52	2735	41	13	430	2000	1865
12/ 3 - 10/ 4/81	2580	390	27	0	550	3170	2370
10/ 4 - 8/ 5/81	990	415	12	6		3550	4640
8/ 5 - 3/ 6/81	309	277	39	13	450	50	320
3/ 6 - 7/ 7/81	206	834	93	8		1670	9705
7/ 7 - 12/ 8/81	5860	455	162	20	2100	13600	21470
12/ 8 - 11/ 9/81	0	415	12	28		450	150
11/ 9 - 4/10/81	0	127	82	13		270	425
4/10 - 6/11/81	743	390	42	9		5880	7940
	20630	18860	1240	400	6850	42000	86300

* refers to suspended sediment output only

already mentioned canopy effects on the erosivity of rainfall the rate of splash detachment on the valley slopes was related to temporal variations in the occurrence of exposed soil. Most of the exposures of bare soil were caused by the consumption of leaves by earthworms with maximum activity in late summer. In addition, the combination of clayey soils and a rich soil fauna led to a high content of biopores and pipes above the seasonally saturated subsoil causing rapid drainage of the topsoil. Widespread conditions of overland flow on the valley slopes (up to 75 percent of the subcatchment area) occurred several times a year during which the soil material detached in the meantime was transferred to the channel incision. Deposition of transported material at the toe of the slope was thought to be of restricted importance because of the minor amounts of colluvial deposits observed.

The sediment output data of Figure 3 represent suspended sediment data only as no monthly data on bed load yield were available. Total bed load output during the two years of investigations amounted to 6700 kg or only 7.8 percent of the suspended sediment output. Next to this the results of a painted pebble study of average transport revealed that over 90 percent of the total transport occurred during the large flood of July 1981. These facts imply that the suspended sediment output data of Figure 3 will approximate very well the total sediment (suspended + bed load) output data except for the July 1981 period which is underestimated.

The output of sediment is highly variable throughout the year as it is a reflection of both the supply of sediment as the generation of runoff. Summer streamwater samples (May to October) exhibit higher suspended sediment concentrations compared to those from winter; this trend reflects the increased occurrence of intensive convectional rainfall in summer possessing a high erosivity which accordingly induces high rates of splash erosion on valley slopes and streambanks. Indirectly the intense thunderstorms cause extensive overland flow on the valley slopes (able to transport splash detached material) and high peak flows in the stream channel inducing bank scour.

The monthly sediment delivery ratio's calculated from the above delivery and output rates are shown in Figure 4. These values vary between 28 and 347 percent with the tendency of above 100 percent values occurring in summer and below 100 percent values in winter. The mean annual sediment delivery ratio amounts to 103 percent. These values are well above those generally reported in literature (Walling, 1983). The reason for such high sediment delivery ratio's lies in the relative ease with which the supplied material is transported. The weathering material of the Keuper marls is known as being very erodible due to its high susceptibility to slaking and dispersion (Imeson & Jungerius, 1977; Imeson et al., 1984). As a consequence the sediment supplied by the various slope and bank processes undergoes rapid physical and chemical breakdown in the streamwater thereby highly enhancing its entrainability. The almost lack of fine sediment deposits in the streambed justifies this reasoning.

IMPLICATIONS FOR CHANNEL STORAGE

The largest unmeasured factor in this study is the amount of sediment that either was entered or removed from bed storage by aggradation or degradation of the channel as such are extremely difficult to document on short time scales. The data of Table 1 show that total in- and output of sediment were more or less in balance during the two years of study implying that the net effect of changes in channel storage was only of

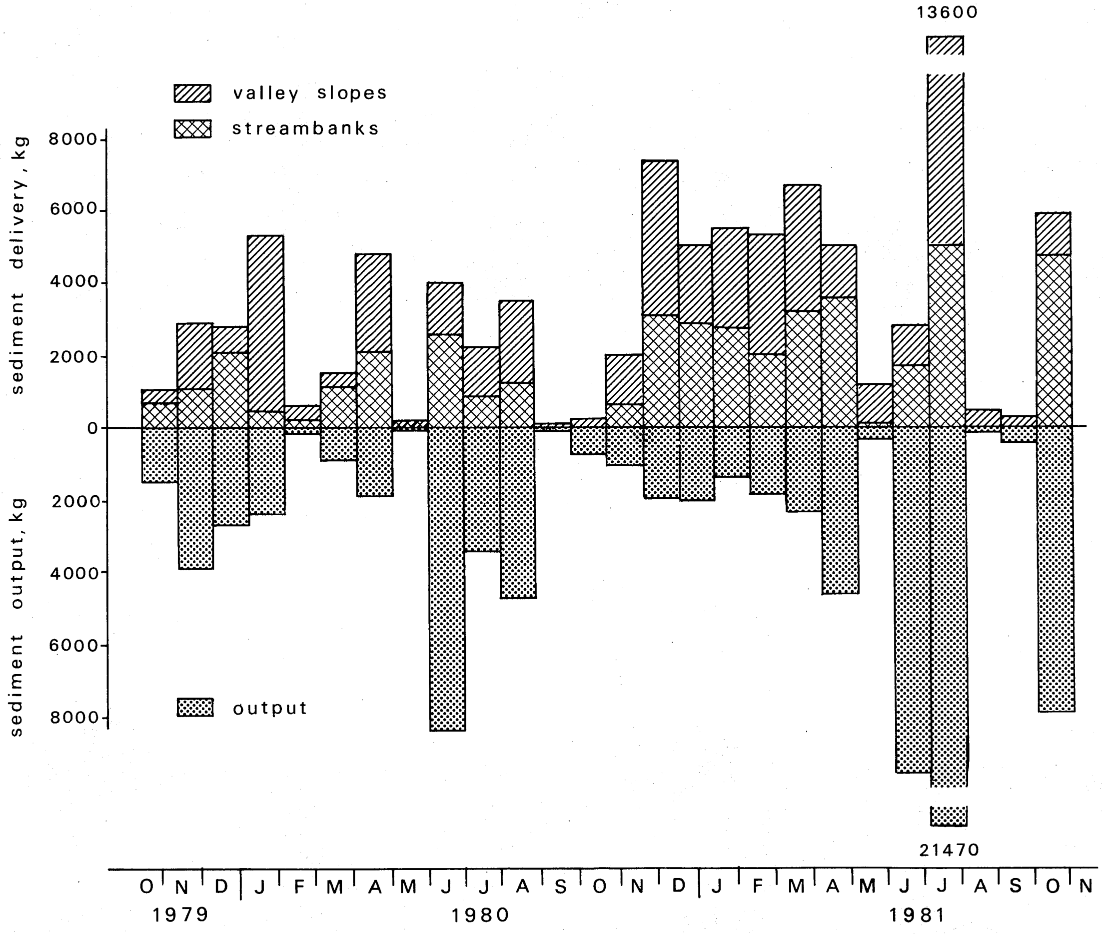

Figure 3 Monthly rates of sediment delivery and sediment output.

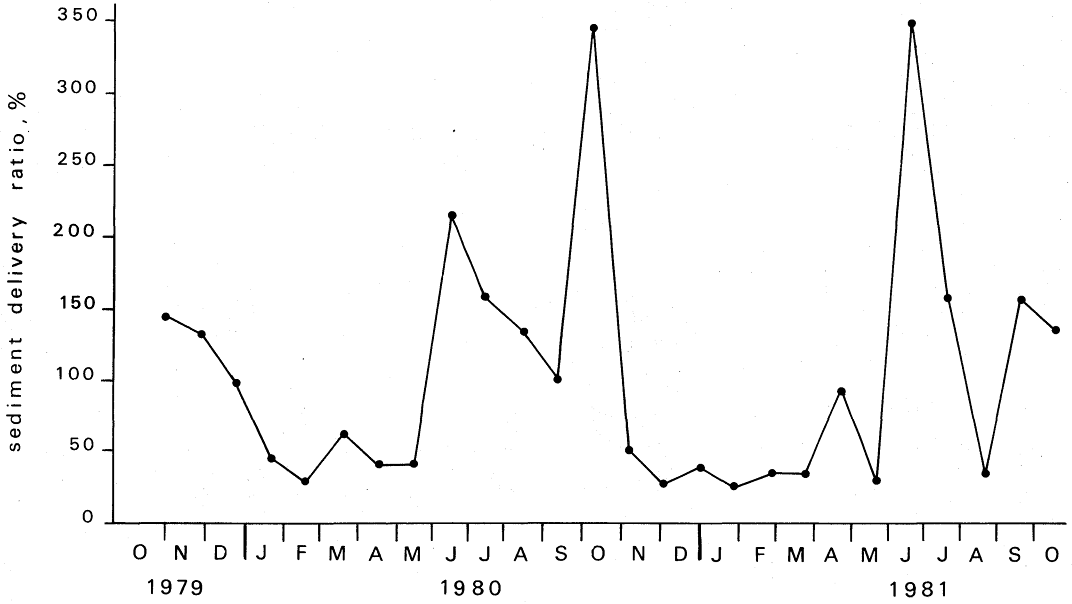

Figure 4 Seasonal variation in the sediment delivery ratio of the Schrondweilerbaach basin.

limited importance. More detailed information on the dynamics of bed storage was obtained by calculating the cumulative changes in sediment storage based upon the net differences between delivery and output (Figure 5). This figure shows a distinct seasonal trend of dominant storage in winter and transport in summer with the consequent highest sediment accumulations during May. It must be realized, however, that the net storage gain between start and end of the period of investigations pictured in Figure 5 has to be corrected for the not included bed load output of 6700 kg (which as was shown above was only of significant importance during the July 1981 measurement interval). The well-defined trend of remobilization of winter stored sediment in summer may also explain part of the higher suspended sediment concentrations as observed in summer.

Next to this seasonal variation in sediment storage grainsize distribution of the transported material was determined and compared with that from the supplied material in order to determine origin of suspended and bed transported material. The resulting frequency distributions are shown in Figure 6 as envelope curves. The curves denote that maximum particle size of suspended material is about 0.25 mm while only about five percent of bed load material is smaller than 0.25 mm. It was assumed then that only the part of the supplied sediment larger than 0.25 mm was stored in the streambed while the corresponding smaller particle sizes left the catchment as suspended load within the study period. Consequently suspended load comprised 100 percent of the sediment supplied from the valley slopes, 95 percent of the amount supplied by rainsplash and creep, 90 percent of subsoil fall, 80 percent of scour and an estimated 75 percent of the amount contributed by bank failures resulting in a total amount of 82000 kg. This estimate implies that about 8000 kg of "coarse" material or nine percent of the supplied material may have been stored in the channel bed. This value agrees very well with the measured bed load output of 6700 kg.

The close resemblance of delivery and output both of suspended sediment and bed load (and the consequent net changes in channel storage) clearly implies that the stream system is very efficient in transporting the supplied sediment. It too denotes a steady state of sediment transfer throughout the basin. The relatively large amount of coarse material stored in the channel bed: 200 - 250 m^3 when compared with the present bedload output of 4.4 m^3 in two years, however, denotes the lack of such steady state conditions during former periods. These data in combination with the already mentioned fact of overestimated bed load transport during the measurement period refer to the existence of higher supply rates (of coarse material) in the past. Such conditions may have existed in a period of stream adjustment following the drainage operations in 1928 (Duijsings, 1985). Lack of maintenance of the dugged ditches and a gradual adjustment of the stream channel to the changed conditions of sediment delivery and transport accordingly resulted in the present phase of sediment transfer.

CONCLUSIONS

The Schrondweilerbaach basin is characterized by a sediment delivery ratio of near 100 percent. The high value of this ratio is largely controlled by the hydrological characteristics of the basin (extensive overland flow, high peak flows) and the erodibility and entrainability of the supplied material.

Sediment is predominantly delivered from streambanks and valley slopes in almost equal amounts. The large number of processes active in

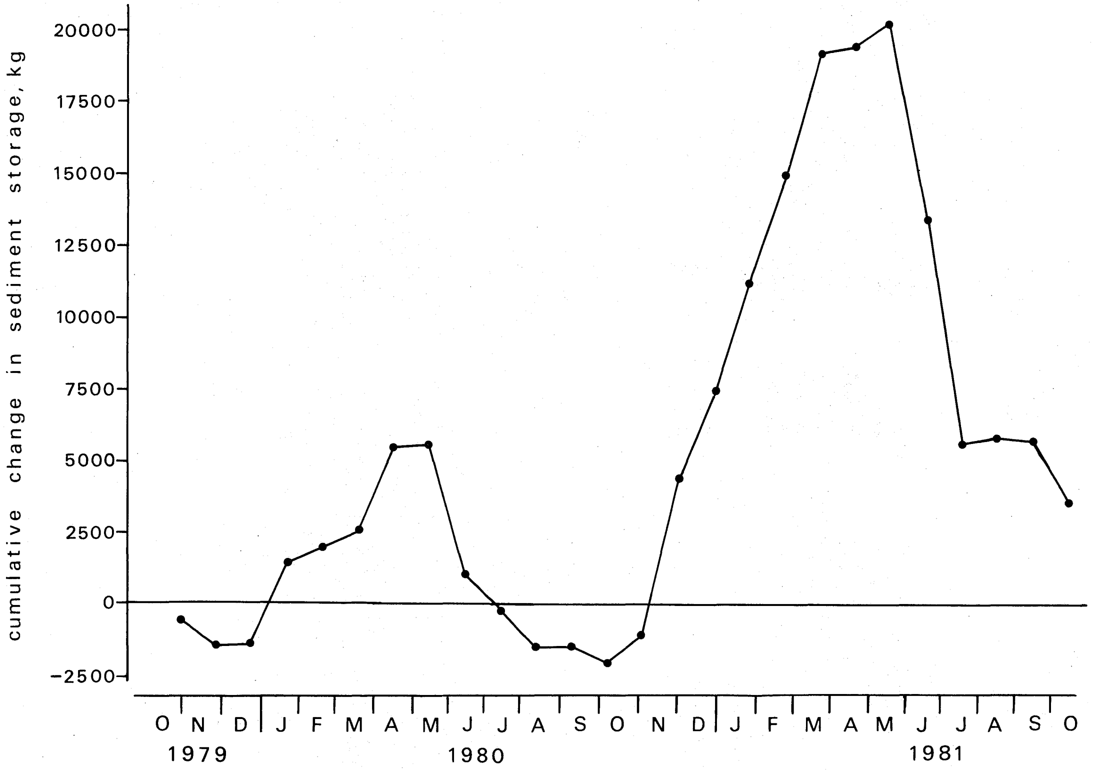

Figure 5 Cumulative change in channel stored sediment.

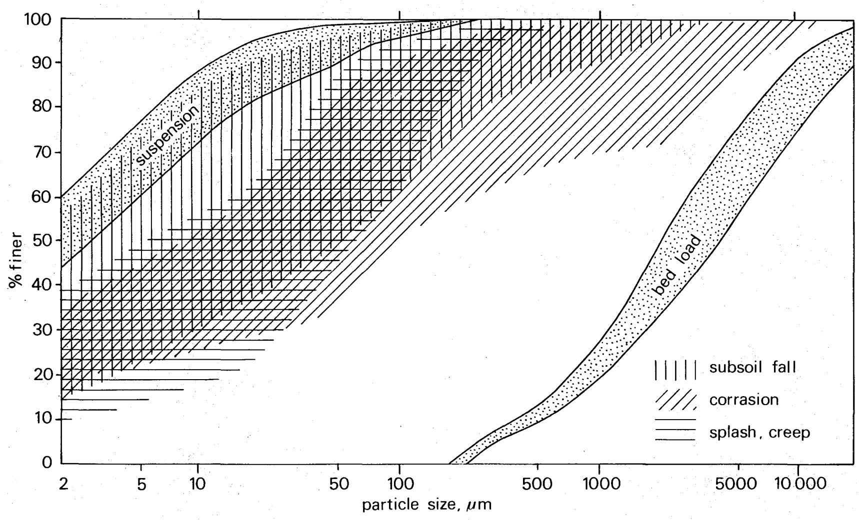

Figure 6 Cumulative grainsize frequency "zones" for the different modes of sediment supply and sediment transport.

sediment production in these source areas - each connected with their typical controls and pattern of sediment supply - cause widely varying sediment delivery rates throughout the year. On a general basis delivery of sediment is at its maximum during winter. Sediment output mainly occurs as suspended load and reaches its maximal values during summer thunderstorms. The monthly sediment delivery ratio's calculated from these delivery and output rates accordingly show a large variability too: about 25 - 50 percent in winter and 100 - 350 percent in summer.

The seasonal trend in the sediment delivery ratio implies the existence of a seasonal trend in sediment storage: net gain in storage during winter and remobilization of stored material (up to the pre-winter volume) during summer. The close similarity of the annual amounts of sediment involved in delivery and output both for suspended and bed load denote the efficiency of the stream in sediment transport. Such is closely related to the physical and chemical characteristics of the supplied material (and the streamwater) which is easily broken down upon the immersion in water. Detailed investigations into residence times of stored material, however, would be needed to study the sediment transfer through the storage compartment in more detail.

Apart from the results above the widely varying sediment delivery and transport rates through time imply a complex response of the basin to rainfall, frost and biological controls. Such complex response denotes the failure of producing general applicable prediction equations and stresses the need for more developed models of sediment transfer.

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