Sediment Budgets in Forested and Unforested Basins in Upland Scotland

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ABSTRACT

The downstream impact of afforestation and deforestation is being studied in paired basins, one forested (6.8 km²) and the other moorland (7.7 km²), at Balquhidder in the steep wet Scottish Highlands. Preliminary sediment budgets are given based on three years' output data and one year's source data. Suspended sediment output from the forested basin varies more closely with water discharge, and is three times higher in total, than that from the moorland basin where it is deduced that less sediment is available. The delivery ratio from first order tributaries to mainstream outlet is close to 1.0 for suspended sediment in both basins, and for bed load in the forested basin, but much lower for bed load in the moorland basin; this presumably reflects channel storage but this has not yet been detected in cross section surveys because bed load fluxes are very low. Mainstream bank erosion accounts for less than 5% of sediment outputs and a landslide into the moorland mainstream in 1985 has not yet affected basin output.

INTRODUCTION

In the United Kingdom two thirds of the surface water storage reservoirs are in the cool, wet uplands of the west and north. Traditionally these undeveloped tracts of land have yielded abundant pure water for supply or power generation. In recent years doubts have arisen concerning the effects of land development, particularly that for plantation forestry (Blackie and Newson, 1985). Because forest establishment requires cultivation and drainage, often on steep slopes, the effect of these operations upon sediment yields (notably bed load) has been a continuing theme of basin studies by the Institute of Hydrology (Newson, 1980). The potential effects of increasing sediment yields in such streams include destruction of fisheries and sedimentation of minor engineering structures within the upland margin. Lower down the river system a delayed impact may occur on channel stability; in predicting such downstream impacts information about the delivery ratio and processes controlling it is crucial. Storage phenomena are likely to play a key role judging from results already obtained in the Institute's Plynlimon basins in mid-Wales (e.g. Arkell et al., 1983; Moore and Newson, 1986).

In order to consider the effects of land use change on runoff and water quality under the harsher conditions of relief and climate prevailing in Scotland the Institute has established the Balquhidder basins (Figure 1; Table 1). Instrumentation began in 1982 under existing land uses: moorland (coarse natural vegetation) in the Monachyle basin and a substantial cover of coniferous forest in the Kirkton basin. In 1986 felling in Kirkton is scheduled to begin and at the same time the Monachyle, with the exception of the upper control area, will be ploughed, drained and planted with trees. This paper reports on sediment yield

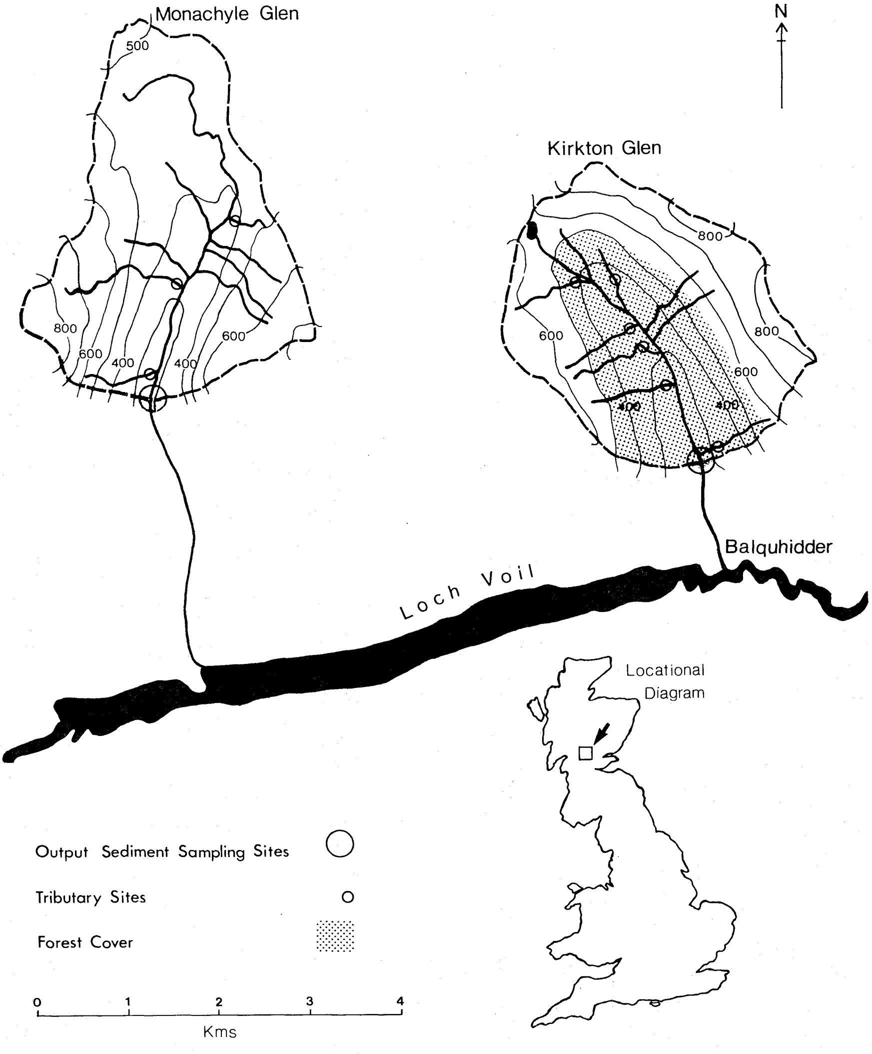

FIGURE 1: Location map showing the Balquhidder paired basins.

measurements to date (end of 1985) in order to calibrate sources, storage and outputs of sediment from both systems. The effort represents collaborative research between a government institute and a university. The University of Stirling's efforts are devoted to investigating sources and pathways for sediment output whilst the Institute measures basin outputs of both water and sediments.

MEASUREMENT METHODS

Sediment sources

Hillslopes in the moorland basin are densely vegetated by heathers, grasses and mosses while those under the forest are either

TABLE 1: **Characteristics of the Balquhidder basins.**

Basin Name	Monachyle	Kirkton
Area (km^2)	7.70	6.85
Forest cover (%)	0	40
Relief (m)	607	623
Stream frequency (km^{-2})	5.1	3.7*
Rainfall** ($mm\ yr^{-1}$)	2100	1900

* not including forest ditches
** for climatic data on the area see Johnson (1985)

overlaid by a thick layer of conifer needles or are vegetated with grasses and *Polytrichum* spp. moss in clearings. Sediment contribution from the hillslopes in the form of washload is considered to be negligible. At the start of the sediment source study in autumn 1984 there was evidence of old revegetated landslides in both basins, and some recent mass movements were apparent on the sideslopes of the moorland glen downstream of the gauging station. However, in view of the apparently low or negligible rates of hillslope processes, and the short time available before land use conversion, no systematic monitoring of hillslope sediment contribution was conducted.

The basins have high drainage densities by U.K. standards with many steep first or second order tributaries. In places these flow over exposed bedrock but lower on the valley sides these are mainly incised up to 1 m into till which appears to be a source of both coarse and fine grained sediment. Simple timber check dams lined with nylon netting of mesh size 2.8 mm were installed in six tributaries in the forested Kirkton basin and three in the moorland Monachyle basin (see Figure 1). These bed load traps are emptied regularly by hand. The mass of trapped sediment has been estimated as the product of number of bucketfulls of sediment removed, bucket volume, and the bulk density 1.37 t m^{-3} estimated from sample bucketfulls. Subsamples were retained for size analysis by sieving. Some material finer than 2.8 mm settles out in the trap pools and some is caught by the netting at times when it has become clogged by organic debris. Since the trap efficiency for material finer than 2.8 mm is unknown (and probably variable) the catches are calculated both with and without the fine fraction.

Pebble tracing experiments were conducted in one moorland tributary and one forested tributary of similar size and gradient to gain some indication of travel distances of bed load and by implication the natural storage opportunities that are present. About 130 pebbles were painted in each stream and grouped into six size classes from 22-32 mm to 128-180 mm.

Several hundred water samples for determination of suspended sediment concentration were obtained during 1985 in four forest tributaries and one moorland tributary, using automatic vacuum-pump samplers with 3 mm diameter inlet hoses positioned at a fixed height above the streambed and pointing downstream. In most cases the samplers were triggered by float switches so the concentrations are representative of above-average discharges.

Sediment sources and sinks along the main stream in each basin were investigated in two ways. About 5 km of the moorland stream, and 2 km of the forest stream, have banks of erodible till or alluvium and in places, notably the outside of meander bends, these are clearly eroding. Over 500 erosion pins constructed from 5 mm galvanised fencing wire were installed at a vertical spacing of 10 cm at sites about 50 m apart along the channels. Changes in pin protrusion were measured at three-monthly intervals from October 1984 onwards. Secondly, an attempt was made to estimate any net change in channel bed storage by periodic resurveys of 30 cross sections in alluvial reaches of both main streams. The sections were levelled to a height accuracy of 1 cm on each occasion, but because of the pebbly nature of the bed it seems doubtful whether scour or fill of less than 10 cm is genuine and not just a reflection of the roughness of the bed.

Sediment output

In the Plynlimon study of bed load yields from forestry and grassland (Newson, 1980), concrete traps were used to obtain bulk sediment yields, information on sources and stores upstream coming from tracer experiments. However, at Balquhidder there was insufficient capital and labour to construct traps at the outset of the study; instead, careful monitoring of the build-up of bed load in the pools of the rectangular gauging weirs has given an approximate measure of bulk yield. The emphasis of bed load measurement at the outlets of Kirkton and Monachyle has passed to gauging instantaneous sediment movement by modified Helley-Smith samplers. Originally a 3-inch (76 mm) orifice was used, as suggested by Helley and Smith (1971). At normal flood flows this proved adequate for the bed load in motion (D_{50} = 1.4 - 11 mm) but because of the coarseness of the bed material in these basins (D_{50} of flood deposits = 64 mm) difficulties were anticipated with the field use of the original design of sampler and a modified sampler was constructed (Bathurst, Leeks and Newson, 1985). This has a six-inch (152 mm) orifice but retains the expansion factor of the original design. Its 'box-kite' tail fin and wading rod suspension make it much more convenient for use by a single operator.

Once collected, Helley-Smith samples are dried, weighed and sieved at the small on-site laboratory at Balquhidder. By providing instantaneous rates of sediment transport it is also hoped that results can be used to improve sediment transport prediction in a way which is impossible with conventional trapping. It is also possible to investigate the movement of coarse organic material, likely to be of importance in studies of afforested basins.

Measurements of fine sediment transport at the outlets have been made with USDH samplers, with backup from automatic pumping samplers of the same type used in the tributary streams. Samples of water and suspended sediment are filtered in the Balquhidder laboratory using the same type of filter membrane as in the analysis of tributary samples done at Stirling University.

RESULTS

Sediment sources and sinks

Total bed load catches from April to December 1985 in six forest tributaries (basin area ranging from 0.1 to 1.2 km^2) correspond to a mean yield of 2.4 t km^{-2} yr^{-1} from 41% of the total basin area. The yields for individual tributaries range from 0.2 to 17 t km^{-2} yr^{-1}. Substantial seasonal variation was also found, broadly in accordance with rainfall amounts. Sieving of sub-samples of the trapped bed load indicated that 44% was finer than the 2.8 mm mesh size of the netting lining the traps, as a result of frequent clogging of the netting by organic material. When only sediment coarser than 2.8 mm is considered the mean tributary bed load yield comes down to 1.3 t km^{-2} yr^{-1}.

Amounts of bed load trapped in three moorland tributaries (basin area ranging from 0.2 to 0.5 km^{2}) corresponded to yields from 0.1 to 4.5 t km^{-2} yr^{-1}, with a mean yield when all three are pooled of 2.0 t km^{-2} yr^{-1} from 15% of the total basin area. From sub-samples, only 12% of the trapped sediment in these streams was finer than 2.8 mm, giving a coarse sediment yield of 1.8 t km^{-2} yr^{-1}. Evidently there is no great difference between moorland and forest in average tributary yields of coarse bed load. Whether the greater amount of $<$ 2.8 mm sediment trapped in the forest streams indicates a greater supply of this fraction, or just a difference in trap efficiency because there is more organic debris to clog up the netting, is not clear.

Some 65% of the tracer pebbles were recovered in a survey 4 months after emplacement. Overall mean distances moved were 3.3 m in the forest tributary and 9.0 m in the moorland tributary. The smallest size class (22-32 mm) showed no significant difference in mean movement. Larger size fractions showed no systematic fall-off in mobility with increasing size in the moorland stream, but a pronounced one in the forest stream. This is not because fewer large pebbles were entrained in this stream but because they were more readily redeposited after a short distance. This is largely a result of organic debris jams in the forest tributary. Surveys of two forest tributaries of average gradients 0.22 and 0.38 showed nine such dams in 400 m and seven in 550 m, or on average 18 km^{-1} which is within the range found in the northwestern U.S. (Madej, 1982, Megahan, 1982).

Only provisional estimates of suspended sediment yield from tributary basins can be given since water levels have not been continuously monitored. Estimates were obtained by multiplying the arithmetic mean concentration for each tributary by its mean discharge, which was estimated from the product of basin area and annual rainfall less an allowance of 300 mm for evapotranspiration. If sampling were random over time the estimated yield would be biased below the true value to the extent that suspended sediment concentration is positively correlated with discharge (Ferguson, 1986b). Against this, the mean concentration calculated is for samples collected during minor and major floods. This is undoubtedly biased upwards and will therefore tend to cancel out the first bias. The mean of 579 concentration values for the forest tributaries totalling 2.1 km^{2} is 89 g m^{-3} (= mg l^{-1}) with standard error 7 g m^{-3}; this gives a provisional yield estimate of about 140 t km^{-2} yr^{-1}. The mean of 119 concentration values for a moorland tributary of basin area 0.2 km^{2} is 23 + 3 g m^{-3}, corresponding to a yield of about 40 t km^{-2} yr^{-1}.

The initial assumption that direct sediment contributions from hillslopes to channels are negligible in the Balquhidder basins was shattered by the occurrence of a shallow landslide in the moorland basin during heavy rain in September 1985. An estimated 36 m^{3} or 65 t of sediment was removed from the scar. This travelled some 500 m down a minor tributary gully to the main channel where a cone containing an estimated 14 t of coarse sediment (D_{50} = 32 mm; 10% finer than 2.8 mm) was still present 12 days later. Some of this fresh sediment was visible on the bed of the main channel for up to 100 m downstream but most of the discrepancy between the headcut and cone volumes is due to deposition in or alongside the slide track before reaching the main channel.

The dispersion downstream of the sediment slug was apparent in some aggradation of the first 2 levelled cross sections downstream over the interval 30 May to 27 September 1985. All other cross sections on main channels showed no aggradation or degradation beyond the 10 cm detection limit imposed by the roughness of the bed; all that can be concluded is that there is no sign of systematic change in the amount of coarse sediment stored in the channel bed.

Five erosion pin surveys along the banks of both main streams betweem October 1984 and December 1985 indicated mean retreat rates of 4 to 19 mm per three months, with standard errors varying between 1 and 3 mm. Both basins showed a similar seasonal pattern with maximum bank retreat in January to March and October to December 1985. The latter was a time of high rainfall (but so was October to December 1985 when less bank retreat was observed), while January to March is a time of low streamflow because most precipitation falls as snow. Bank erosion at this time is attributed largely to frost action on fine-grained bank materials, which has been found to be important in other British studies (e.g. Lawler, 1986). Rates of bank retreat were substantially higher in the moorland channel (mean = 62 mm yr^{-1}) than in the forest channel (mean = 43 mm yr^{-1}); it is possible that this reflects the attenuation of both air frost and stream rise and fall under a forest canopy. The estimated area of eroding banks along each stream is similar (250 and 240 m^2), as is the measured bulk density of fine bank material (1.04 and 1.16 t m^{-3}), so the total sediment supply from mainstream bank erosion is greater in the moorland basin (17 t yr^{-1}) than in the forest basin (11 t yr^{-1}). 93 and 72% of the sediment supplied from moorland and forest banks respectively is finer than 2.8 mm. The totals involved are an order of magnitude smaller than the provisional estimates of suspended sediment yields from tributary streams, so mainstream bank erosion would not seem to be a major source of fine sediment.

Sediment output

Data collected since 1982 amount at the time of writing to about 150 samples of bed load and 750 of suspended sediment. In both cases it was initially thought desirable to divide samples into seasonal groups, and subdivide these according to rising or falling state of streamflow at the time of sampling, before fitting separate rating curves for use with flow duration records. However, as yet there are too few samples of bed load, and suspended load in winter, spring and summer, to permit a rising/falling stage split. The seasonal division is not rigidly defined but is decided each year by the Institute's resident observer on the basis of changes in measured rainfall, snowfall and air temperature. Generally though, winter is December to March, spring is April and May, summer is May through August and autumn is September to December.

Rating curves for suspended and bed load in different seasons in both basins are compared in Table 2. The winter suspended load rating for the forest basin is based on very few samples since precipitation falls mainly as snow and the streams are low; it is not statistically significant and clearly load calculations using it will be unreliable. In all other seasons the forest rating curves are significantly steeper than those for the moorland stream, and the scatter about them is in all cases smaller. This contrast can be explained by a greater availability of sediment within the plantation forest. This would confirm the Plynlimon findings and those of the source area studies above. It seems that fine sediment in forest ditches and organic debris jams is flushed out by high flows so that there is less scatter in the relationship between load and flow and a steeper growth of load with rising flow than in the moorland basin where there are few obvious sources of fine sediment. The bed load rating curve for the forest basin also has less scatter about it than the moorland rating, but the contrast in slopes is reversed: the moorland rating is steeper, though not significantly so.

TABLE 2 Rating curves of sediment load on discharge for Balquhidder basins, 1982-5

		Monachyle (moorland)				Kirkton (forest)			
type	season	n	b±se	r	s	n	b±se	r	s
Suspended Sediment load	Autumn, rising	60	1.72±.19	.59	.59	60	3.12±.18	.84	.18
	Autumn, falling	60	1.12±.15	.48	.52	60	3.85±.21	.86	.31
	Winter	54	1.78±.11	.83	.41	14	(0.25±.31)	(.05)	.23
	Spring	50	1.33±.17	.57	.51	37	1.95±.25	.64	.49
	Summer	60	1.14±.15	.50	.62	37	2.67±.34	.64	.56
bedload	all	60	2.40±.19	.74	.55	60	1.88±.27	.45	.28

Key: n = sample size, b = exponent in $\log_{10} L = a + b \log_{10} Q$, L = load in gs^{-1},
Q = discharge in $m^3 s^{-1}$, se = standard error of b, r = correlation coefficient,
s = standard error of estimate, ( ) = not significant.

TABLE 3 Outputs of suspended sediment and bedload from the two basins, 1982-5, based on rating curves of Table 2 and seasonal flow duration curves. Raw estimates are given in brackets followed by those corrected for logarithmic rating bias. Starred figures are unreliable: see text for explanation

	Season	Monachyle (moorland)	Kirkton (forest)
Suspended Sediment load (tonnes)	Autumn, rising	(71) 179	(290) 316
	Autumn, falling	(91) 188	(440) 571
	Winter	(92) 144	(983) 1129*
	Spring	(41) 83	(47) 90
	Summer	(25) 69	(234) 530
	total	(320) 663	(1994) 2636*
Suspended sediment yield (t km^{-2} yr^{-1})		(18) 38	(99) 131*
bedload total (tonnes)		(0.9) 2.1	(34) 42
bedload yield (t km^{-2} yr^{-1})		(0.05)0.12	(1.69)2.09

Total loads of sediment leaving each basin have been estimated by combining the rating curves of Table 2 with the appropriate seasonal flow duration data based upon five-minute recordings of water level. The harsh winter conditions at Balquhidder have caused some gaps in the flow record but these are mainly during conditions of heavy icing when sediment transport is probably minimal. Since the scatter about the log-log rating curves for both suspended and bed load is considerable, and this causes a systematic bias in the direction of underestimation of the true load (Ferguson 1986a,b), the correction factor proposed by Ferguson (1986a) has been used to give more nearly unbiased estimates of seasonal totals of sediment output in the 1982-1985 period. The raw and corrected results are listed in Table 3.

In all seasons the forested basin yields more sediment: on an annual basis per unit area, and using the bias-corrected figures, over three times as much suspended sediment and almost 20 times more bed load. It is somewhat surprising to find suspended load dominating. At Plynlimon suspended load contributes 49% and 24% of total load in the grassland and forest basins respectively. At Balquhidder the respective figures are 99.7% and 98.4%.

As a check on the bed load yield figures it is instructive to consider the rate of filling of the weir pools. In the Kirkton weir this has been sufficiently rapid to require mechanical clearing of the deposits in the interest of gauging accuracy. A total of 42 t of sediment has been removed in three years, equivalent to 14 t yr^{-1} or 2.0 t km^{-2} yr^{-1} which is in good agreement with the bias-corrected figure from Helley-Smith samples. In practice, both systems of measurement will tend to underestimate yield because of imperfect trap efficiency. However, the similarity of the two estimates is encouraging as is the observation that bed load accumulation in the weir pool of the Monachyle structure during the same period has been small enough not to require clearing (one would estimate just over a tonne using the rating approach).

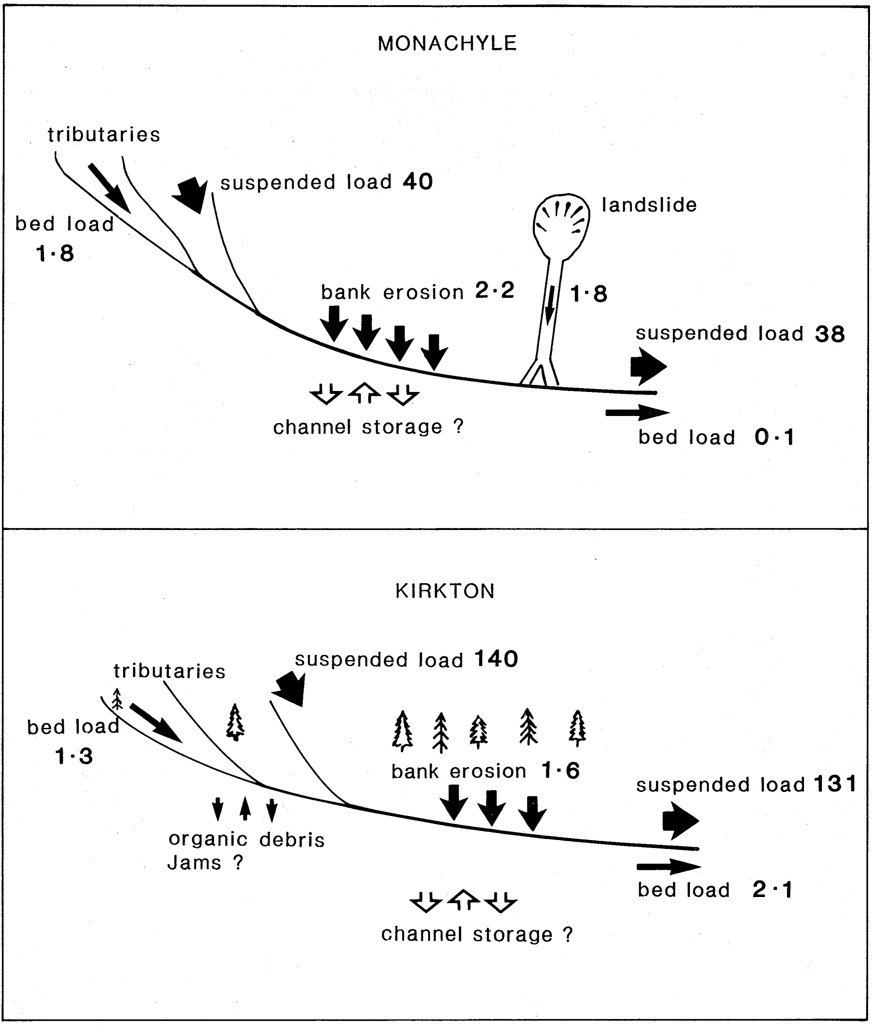

FIGURE 2: Schematic sediment budget for the Balquhidder basins based on 1985 sources and 1982-1985 outputs. All figures are yields in $t\ km^{-2}\ yr^{-1}$ averaged over the whole basin area. Outputs are calculated using bias correction, tributary bedload is > 2.8 mm only.

DISCUSSION AND CONCLUSIONS

Figure 2 is a schematic sediment budget for the Balquhidder basins based on 1982-1985 output data and 1985 source data. Whilst there are large margins of error in the calculations of both inputs and outputs of fine sediments, there is an approximate agreement between the supply from tributaries and its transport out of the basins (i.e. a delivery ratio close to 1.0). There is also a relatively high delivery ratio between source area and basin outputs of bed load in the forested basin. In the moorland basin, however, the delivery ratio for bed load is much lower implying that most bed load from tributaries is stored in the main channel. The same is true of the landslide contribution in this basin which occurred right at the end of the sediment output measurement period and is therefore not yet reflected in the basin output estimate. The frequency of such an event is estimated at somewhere upwards of 10 years so its long term average importance is probably less than suggested in Figure 2.

Although the delivery ratio of tributary bed load in the moorland basin is low, the amount of channel storage implied is also low, and therefore hard to detect. The tributary yield of 1.8 t km^{-2} yr^{-1} corresponds to only 13 t yr^{-1} of aggradation along a mainstream of length more than 1 km and average width of 5 m, i.e. a mean aggradation rate of about 1 mm yr^{-1}. It is not surprising that this has not been detected by resurveys of channel cross sections. Some storage must occur. For instance, the D_{50} for bed load reaching the basin outlets (3.5 mm in the moorland basin and 1.0 mm in the forest basin) is finer than that supplied in source areas (32 mm in the moorland traps and 8 mm in the forest traps estimated from 17 and 44 sub-samples respectively). Obviously much coarser material is capable of being transported in the two channels. Flood deposits in both basins have a D_{50} of about 64 mm. Have major floods in the period been missed? Taking the maximum flows sampled for bed load yield at the basin outlets, these have been exceeded for 0.5% (Kirkton) and 0.3% (Monachyle) of the entire existing record. One is clearly left with the conclusion that channel storage of the coarser clasts must be an important process until a low frequency event produces an evacuation of this stored material.

The calculated sediment yields for the Balquhidder basins require putting into the context of published figures for Britain. Newson (1986) suggests that yields of bed load from mountainous or disturbed upland basins are anomalously high in relation to basin area. Both Kirkton and Monachyle bed load yields are, however, unexpectedly low. In contrast, it is their suspended load yields which are anomalously high. Duck (1985) has pointed to the major impact of disturbance on suspended loads in a nearby stream and it may well be that bedrock, drift and soil factors in this part of the Highlands explain the relative proportions of the two forms of sediment transport.

There are also some clear methodological conclusions from this work:

(a) Although bed load trapping is the most suitable technique for channel source areas and Helley-Smith sampling is most suitable for larger basin outlets, there are obvious problems in reconciling the two types of data with complete certainty. In this study the existence of ad hoc traps in the gauging weir pools has supported the estimates made from Helley-Smith sampling. Clearly, recording traps offer an attractive alternative (Reid et al, 1985).

(b) It is clearly desirable to improve the seasonal rating curves for suspended sediment loads in the basins. The corrections applied probably make the estimated loads more accurate but rising and falling subdivision should be an aim for all seasons, backed by continuous records through floods to detect exhaustion effects. Further bed load samples are required at the highest flows.

(c) The harsh and unusual climate of Balquhidder invalidates the use of standard seasons in sediment studies. There are particular problems of successful data collection in winter and these unfortunately impair the utility of automatic samplers and turbidity meters.

(d) The relatively small fluxes of material make direct assessments of storage changes difficult. Further progress in using the existing data set must inevitably involve routing sediments by size class over common time bases: seasonal variability is of obvious importance.

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