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Changes in the sediment output of two upland drainage basins during forestry land use changes

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Abstract As part of an experiment to investigate the environmental impact of forestry at Balquhidder in upland Scotland, sediment discharges have been monitored during the felling of a coniferous forest in one basin and ploughing/planting in another. Sediment sampling techniques are described including the determination of an optimal sampling point. The influence of different sediment generating processes on the supply of mobile material is assessed by determining seasonal influences. Average annual yields prior to the land use changes were 56 t km^{-2} from the forested basin and 37 t km^{-2} from the moorland basin. For the period after the land-use changes loads are shown to have increased by 5 and 3 times respectively. Sources are now dominated by forestry roads and plough furrows.

Modifications dans la production de sédiments de deux bassins versants des hautes terres à la suite de modifications dans l'utilisation des sols (déforestation ou création de forêt)

Résumé Constituant une des parties d'un ensemble expérimental en vue de la recherche de l'impact de la constitution d'une couverture forestière à Balquhidder, sur les hautes terres d'Ecosse, la surveillance des transports de sédiments a été organisée pendant l'abattage d'une forêt de conifères sur un bassin et le labour et la plantation sur un autre. On décrit la technique d'échantillonnage de sédiment y compris la détermination du point optimum de prélèvement. L'influence des différents processus libérant les sédiments sur la fourniture de matériaux mobiles est établie en déterminant les influences saisonnières. Le taux annuel moyen d'érosion avant modification de l'utilisation des sols était de 56 t km^{-2} pour le bassin sous forêt et de 37 t km^{-2} pour le bassin couvert de landes. Pour la période après modification de l'utilisation des sols, les charges solides ont été multipliées respectivement par 5 et 3. Les origines des sédiments sont maintenant principalement les routes forestières et les rigoles de labour.

INTRODUCTION

Forestry has developed into a major land-use in Great Britain over the past 40 years. The area of productive woodland reached two million hectares by 1987 (Forestry Commission, 1987), with most of this being in upland areas. The industry recently reached a significant stage in its development by starting the clearfelling of the first forest cycle coincident with changes in recommended forestry practices which show greater concern for the environment. Due to the harsh climate, rugged terrain and thin soil cover, the region in the UK potentially most easily disrupted by forestry is Scotland where recently the industry has been expanding at a greater rate than in England or Wales. The Institute of Hydrology established two research drainage basins at Balquhidder in 1981 to assess the effect of forestry in the highlands of Scotland. Water quantity and quality data have been collected through several phases of the forestry cycle.

The greatest impact forestry has on water quality is the increased sediment loads in the rivers. This is well documented in other UK work e.g. Robinson & Blyth (1982), where loads were shown to have increased by four times after pre-planting drainage. The only other work currently being done in the UK on changes in sediment discharge rates due to clearfelling is a study in Wales where loads increased by two times (Leeks & Roberts, 1987). Balquhidder represents the first long term study in Scotland on the effects of both clearfelling and cultivation using the current recommended forest practices.

THE BALQUHIDDER DRAINAGE BASINS

The two drainage basins (Fig. l), Kirkton (6.85 km^2) and Monachyle (7.70 km^2), have a relief of over 600 m with an average lateral slope angle of 20°. Drainage consists of many small first-order lateral streams with one second-order main stream in each basin; drainage density is around 4 km km^{-2}. The underlying geology is mica-schist mantled by glacial deposits in lower areas. Soils of peats and peaty-gleys are thin, supporting a vegetation of heather, bilberry and coarse grasses. At the start of the project the lower Kirkton basin (2.88 km^2) also contained a mature (40–50 year old) coniferous forest. A network of old forestry roads existed in the Kirkton plantation, whereas there were no roads in the Monachyle basin.

Land use changed at the end of 1985 when road upgrading and felling started in the Kirkton basin, with some 40% of the forest having been felled by the end of 1987. Timber extraction to the roads was by cable-crane on steep slopes and tracked vehicles driven on brash mats on gentle slopes. Removal of the forest was by logging lorry operating on a frequency of about four loads each day. Road repairs were carried out by bulldozer and grader. In the Monachyle basin, preparation of the land for planting was started in spring 1986. Only 6% of the catchment could be ploughed because of the very steep, wet slopes. Plough lines were perpendicular to the slope terminating some 20 m before the main water course. Cut-off drains with

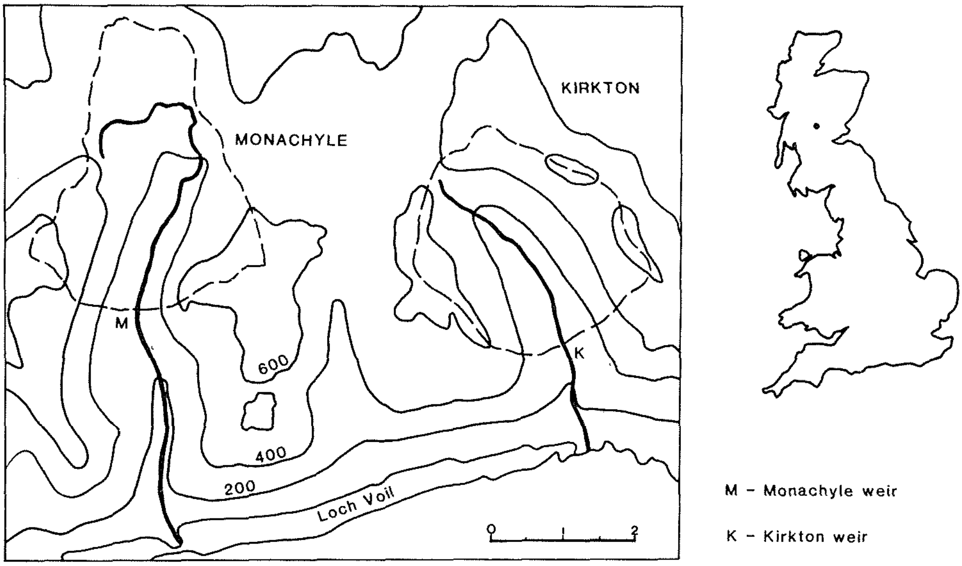

Fig. 1 *Location diagram of the Balquhidder basins.*

slopes of <3° were dug across the ends of the furrows and again terminated well before natural drainage lines.

Annual precipitation totals in the basins average 2400 m with a mean intensity of 1.2 mm h^{-1}. Winter precipitation contains significant amounts of snow, and there are, on average, 185 days each year when some snow is lying on the hills. At a low altitude weather station the average numbers of days of ground frosts is 141.

The flow duration curves for the basins during 1983–1985 showed that the Monachyle basin was more "flashy" with lower base flows. Maximum peak flows were 11.33 m^3 s^{-1} at Kirkton and 15.73 m^3 s^{-1} at Monachyle. Times to peak were similar but recession times were longer in the Kirkton basin.

Sediment sources in the basins have been identified (Stott, 1987) as being primarily the tributaries and, to a lesser degree, mainstream banks. There is a large storage of sediment on the stream beds, probably in a state of dynamic equilibrium. After the land use changes, the new dominant sources were the roads in the Kirkton basin, and the plough furrows in the Monachyle basin.

SEDIMENT MEASUREMENT TECHNIQUES

Suspended sediment concentration is sampled using single point automatic vacuum samplers and depth integrating manual samplers. To ensure that the samples taken automatically were representative of the whole cross section of flow, manual point samples were taken at 0.5 m width intervals across the streams and 0.1 m height intervals from the bed in different flow conditions.

Concentrations were found to be less in the flow above a well armoured bed than a sandy bed, with those samples 0.1 m above the armoured bed being closest in value to the mean of all samples. This therefore became the optimum position when a single point sample was taken.

Bed load is sampled using Helley-Smith bed load samplers (Helley & Smith, 1971) placed in the flow for 10 min durations. Again the optimum sampling positions were determined, using pairs of samplers.

SEDIMENT OUTPUT BEFORE THE LAND-USE CHANGES (1983–1985)

Suspended sediment and bed load were sampled mainly during flood events. This has the advantage of sampling when the flow is most likely to contain the highest sediment loads, but it does introduce a bias towards high flows which are only a small part of the annual flow regime. Rating curves were computed relating suspended sediment concentration and bed load to flow. The magnitude of errors involved in using rating curves can be large, sometimes estimated to be over 50% depending on the catchment and sampling interval (Walling, 1977). In all cases logarithmic relationships have been used with a correction (Ferguson, 1986) applied which, with the scatter and sample size taken into account, reduces the errors to give 100% of the annual load with a standard deviation of 20% (Ferguson, 1987, Tables 1 and 2). Samples have been subdivided according to discharge tendency (increasing or decreasing discharge >0.1 $m^3\ s^{-1}$ over 15 min) and "seasonal" classes (quarters of the calendar year) for further rating curve analysis. The bed load samples were sieved and the total basin load estimated from the size fractions greater than 1 mm to avoid overlap with the suspended sediment samples.

Table 1 *1983–1986 ratings ($\log_{10}C = a + b.\log_{10}Q$) where C = concentration (mg l^{-1}); Q = water discharge ($m^3\ s^{-1}$); r = correlation coefficient; s = standard error of estimate*

	a	*b*	*r*	*s*
Kirkton				
1983	*0.958*	*1.30*	*0.56*	*0.58*
1984	*1.06*	*1.19*	*0.62*	*0.40*
1985	*0.784*	*1.73*	*0.57*	*0.45*
1986	*1.72*	*0.888*	*0.26*	*0.56*
1983–85 bed load	*– 1.11*	*3.00*	*0.74*	*0.60*
Monachyle				
1983	*0.794*	*0.660*	*0.19*	*0.54*
1984	*0.910*	*0.444*	*0.11*	*0.49*
1985	*0.769*	*0.272*	*0.13*	*0.53*
1986	*1.44*	*0.188*	*0.04*	*0.54*
1983–85 bed load	*– 2.27*	*2.48*	*0.76*	*0.54*

Table 2 Annual sediment loads (t)

	Suspended: Kirkton	Monachyle	*Bedload:* Kirkton	Monachyle
1983	*483*	*337*	*6*	*<1*
1984	*292*	*296*	*5*	*<1*
1985	*386*	*228*	*6*	*<1*
*1986**	*1965*	*1027*	*not available*	
*1987**	*986*	*860*	*not available*	

**Provisional figures.*

Figure 2 A and B show the envelopes containing the 1983–1985 data with details of the rating curves given in Table 1. A distinctive feature of the envelopes is the large amount of scatter in the Monachyle and lower flow range of the Kirkton. In the Monachyle this could be attributed to a limitation of supply through the year. However, the seasonal plots show that in the winter there is much less scatter. This is probably a result of the source areas being unprotected by vegetation and subjected to frequent freeze/thaw events, making sediment readily available. Scatter in the summer could be due to infrequent drying and loosening of sediment sources, or the generation of sediment by higher intensity summer rainfall, both limiting supply to irregular events. The Kirkton basin shows a large amount of scatter in the spring with the least in the autumn. Due to the shelter of the trees the effects of freeze/thaw, drying and intense rain are all probably reduced in duration and intensity, and the spring scatter is probably due to release of sediment by only occasional freeze/thaw events. The close relationship of flow to concentration in autumn is probably due to source areas being wet prior to a storm and responding rapidly to storm events.

Surprisingly, unlike in other work in Britain (e.g. Walling & Webb, 1981), there appears to be no difference in the rating equation and scatter between rising and falling stages, indicating that the sources have larger quantities of sediment available than in other experimental basins.

Bed load samples shows a good correlation with flow. They do not include samples in very high flows as the sampler cannot be operated under these conditions. Extrapolation of the rating curve into high flows could be adequate as during one period of almost a year a weir approach filled up with 17 t of sediment and in the same period the rating equation for unsieved samples estimated the load to be 19 t.

Table 2 shows all loads obtained by applying the individual years' ratings to the relevant 15 min flow data. Kirkton annual suspended loads (mean 387 t, 56 t km^{-2}) are greater than those for the Monachyle basin (287 t, 37 t km^{-2}) in two of the three years sampled. Bed load >l mm is a very small proportion of the total load (<2%). The greater loads from the Kirkton basin indicate that it is still in a recovery period from the initial land disturbance, even though the trees now provide shelter to some source areas.

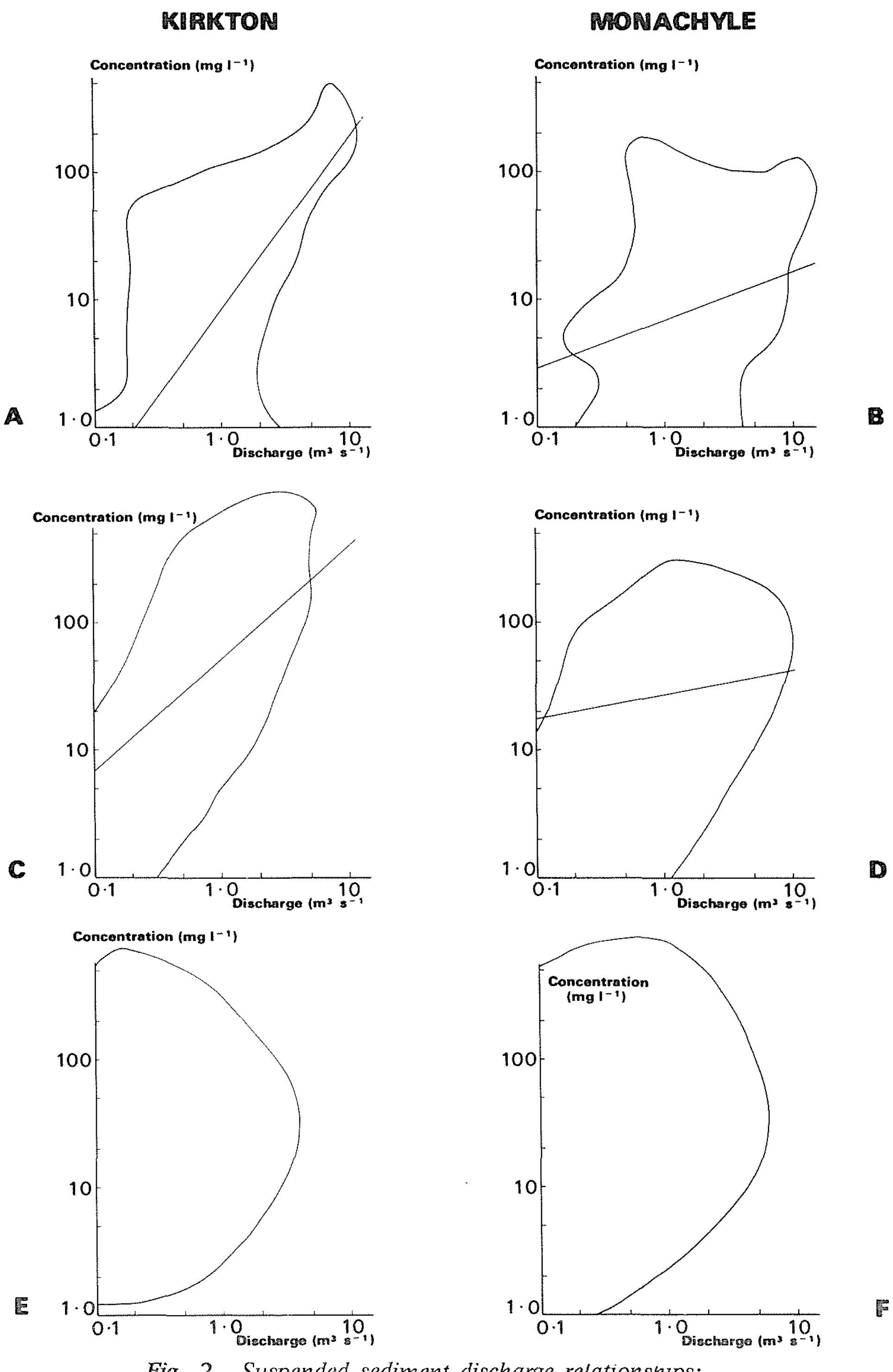

Fig. 2 Suspended sediment discharge relationships: A B 1983–1985; C D 1986; E F 1987.

SEDIMENT OUTPUT AFTER THE LAND-USE CHANGES (1986–1987)

During 1986, suspended sediment sampling was intensified, again concentrating on flood events. Results (Fig. 2 C and D and Table 1) show that the rating curves changed significantly, increasing by an order of magnitude during the lower flow ranges. The scatter of points at low flows had increased, particularly in the Monachyle basin. It is difficult to find any differences between seasons or discharge tendencies in either basin.

Annual loads (Table 2) increased dramatically; in the Kirkton basin by a factor of 5.1 and in the Monachyle basin by 3.6. The primary reason appears to be the large increases in concentrations at flows below about 0.5 m^3 s^{-1} Sediment was much more available at the start of each storm, increasing concentrations even before the flow rose but this increased availability was not so marked at higher flows, as shown by the less steep rating curves. The lack of seasonal differences implies that in each basin there was a new dominant sediment source which was active all year.

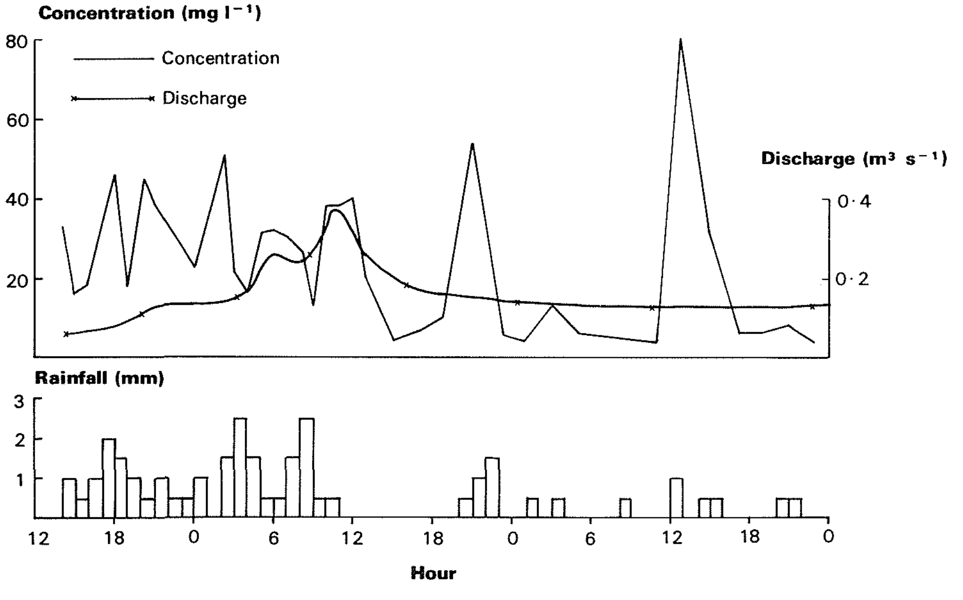

Fig. 3 Kirkton suspended sediment concentration, discharge and rainfall 29–31 May 1987.

The apparently increasing importance of the lower flows prompted a change in the suspended sediment sampling methods in 1987 with automatic samplers being used continuously at 8-h intervals. Figure 2E and F shows a broad envelope of sample points in both basins with no apparent relationship between concentration and flow. Some very high concentrations were sampled; in the Kirkton basin the maximum was 1818 mg l^{-1} and in the Monachyle basin the maximum was 1173 mg l^{-1}, compared to the 1983–1985 maxima of

487 and 188 mg l^{-1} respectively.

From observations of flow in plough-lines and road ditches, it became evident that sediment concentration in these locations was closely related to rainfall and this suspended load was often transmitted into the main streams. Figure 3 gives an example for the Kirkton basin during May 1987 when the sampling interval was reduced. The response to flood events is still evident, but the general pattern is linked more to rainfall with an intensity greater than 1 mm h^{-1}. The likely reason is that the sediment became more available for transport and whereas previously it took prolonged intense rainfall to release and transport sediment to the streams, sediment is now also transported during lower intensity rainfall. These are often conditions which do not significantly increase wi streams' flow, hence the poor correlation of concentration with discharge.

The calculation of an annual load for 1987 by a single flow related rating curve will contain unacceptably large errors, but combined flow and rainfall relationships are being developed. First estimates of annual loads indicate an apparent recovery of sediment discharge, compared to 1986, but the decrease is also due to rainfall in 1987 being 20% down on the 1983–1986 average.

CONCLUSIONS

Before the land use changes the annual sediment output from the Kirkton basin was greater than from the Monachyle basin, due to this basin still being in a recovery period from the initial land disturbance. During the year following the land use changes, the sediment output from the Kirkton basin increased by a factor of 5.1 and that of the Monachyle basin by 3.6 due to the Kirkton roads and Monachyle drainage lines becoming the major sediment sources.

Sediment sources are influenced greatly by the vegetation cover, with a close forest canopy providing shelter against frosts, intense rain and surface drying. These are illustrated by the seasonal differences between the basins. Frosts have more influence in the Monachyle, so that the availability of sediment is increased in winter and spring. Surface drying is more frequent in the Monachyle so that summer availability becomes irregular depending on these drying periods followed by intense summer rainfall. These results show how sensitive the Scottish uplands are to a major land use change such as forestry.

REFERENCES

Ferguson, R. I. (1986) River load underestimation by rating curves. *Wat. Resour. Res.* 22 (1) 74-76. **(Dick, is this reference cited?)**

Ferguson, R. I. (1987) Accuracy and precision of methods for estimating river loads. *Earth Surf. Processes* 12, 95-104.

Forestry Commission (1987) *Forestry Facts and Figures 1986-87.*

Helley, E. J. & Smith, W. (1971) Development and calibration of a pressure-difference bedload sampler. USGS Open File Report.

Leeks, G. J. L. & Roberts, G. (1987) The effects of forestry on upland streams - with special reference to water quality and sediment transport. In: *Environmental Aspects of Plantation Forestry in Wales* (ed. by J. E. G. Good), Institute of Terrestial Ecology Symp. no. 22, 9-24.

Robinson, M. & Blythe, K. (1982) The effect of forestry drainage operations on upland sediment yields: a case study. *Earth Surf. Processes* 7, 85-90.

Stott, T. A. (1987) Forestry effects on sediment sources and yields in the Balquhidder catchments, central Scotland. PhD Thesis Univ. of Stirling, Stirling, UK.

Walling, D. E. (1977) Assessing the accuracy of suspended sediment rating curves for a small basin. *Wat. Resour. Res.* **13** (3), 531-538.

Walling, D. E. & Webb, B. W. (1981) The reliability of suspended sediment load data. In: *Erosion and Sediment Transport Measurement (Proc. Florence Symp., June 1981),* 177-194. IAHS Publ. no. 133.