Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

DISENTANGLING LAND USE EFFECTS ON SEDIMENT YIELD FROM YEAR TO YEAR CLIMATIC VARIABILITY

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ABSTRACT Suspended sediment concentrations (SSC) were monitored over a three year period in two streams in Loch Ard Forest north of Glasgow, Scotland. During the monitoring period one catchment was clearfelled using minimum disturbance techniques, the other remained under forest as a control. SSC maxima in both streams were recorded during a very wet period in early 1988, shortly after the start of felling. SSC in the experimental stream was greater than would be predicted from the larger discharge at this time. A sediment loss of at least 34 t km^{-2} during the first three months was related to this initial bankside clearance in the experimental catchment. Losses during the remainder of the monitoring period were similar in both catchments. Precise estimates of any extra loss due to felling were not possible due to lack of comparability between the experimental and control catchments, to lack of data in the pre-felling phase and to significant temporal variations in sediment losses. The importance of paired catchment selection and of sufficently long monitoring periods is highlighted by the results obtained.

INTRODUCTION

More than 10% of Great Britain has been afforested since 1919, mainly with conifers, and harvesting of the first rotation of the older plantations is gathering pace. A number of studies are under way on the impact of timber harvesting on stream sediment concentrations and yields because of the possible adverse effects on fisheries and rural water supplies. Preliminary results from one Scottish catchment experiment (Johnson, 1988) indicated a five-fold increase in sediment yield after clearfelling, with much of the increase attributable to erosion of logging roads.

In this paper we present preliminary results from another Scottish study. The aim of the study was to quantify suspended sediment yields from two neighbouring forest catchments, one of which was 70% clear-felled during the monitoring period. The felling procedures were aimed at reducing the impact of felling on stream sediment concentrations, by hand-felling and subsequent extraction of felled timber by cable-crane.

FIELD SITES & METHODS

The two streams monitored are headwater tributaries of the River Forth, draining catchments in Loch Ard Forest some 40 km north of Glasgow (Fig. 1). The experimental catchment (no. 10) has an area of 0.84 km^2 and borders the larger (1.51 km^2) control catchment (no. 11). Both streams flow approximately northeast from sources at about 200 m a.m.s.l. to gauging stations at about 100 m a.m.s.l. At the start of the study in 1987, both catchments had a near 100% cover of conifer forest, a mixture of spruces and pines planted in 1954 and 1961. An access road runs along the upper edge of the two catchments, and in late 1986 a spur road for timber extraction was constructed along the southeastern side of catchment 10 close to the ridge dividing it from catchment 11.

Catchment 10 was progressively clear-felled from December 1987 onwards. Initial felling in the first three months of 1988 was confined to the riparian zone. Felling of block I (Fig. 1) began in March 1988 and felling of blocks II and III began in September 1988. Some timber in block IV was felled and extracted in late 1989, but felling of the remaining timber in this block was not considered to be economically viable, and approximately 30% of catchment 10 remained under forest. Felling and extraction of timber from the experimental catchment were effectively completed by the end of 1989.

Discharge was monitored continuously at gauging stations operated by Forth River Purification Board on the two streams, initially by data logger and latterly by chart recorder. Failure of the data loggers during 1987 resulted in an incomplete record of discharge for the important pre-felling phase of the study. Samples for suspended sediment analysis were obtained from vacuum water samplers located close to the gauging stations. Initial sampling was at 2 h intervals during high-flow events, with a second sampler providing

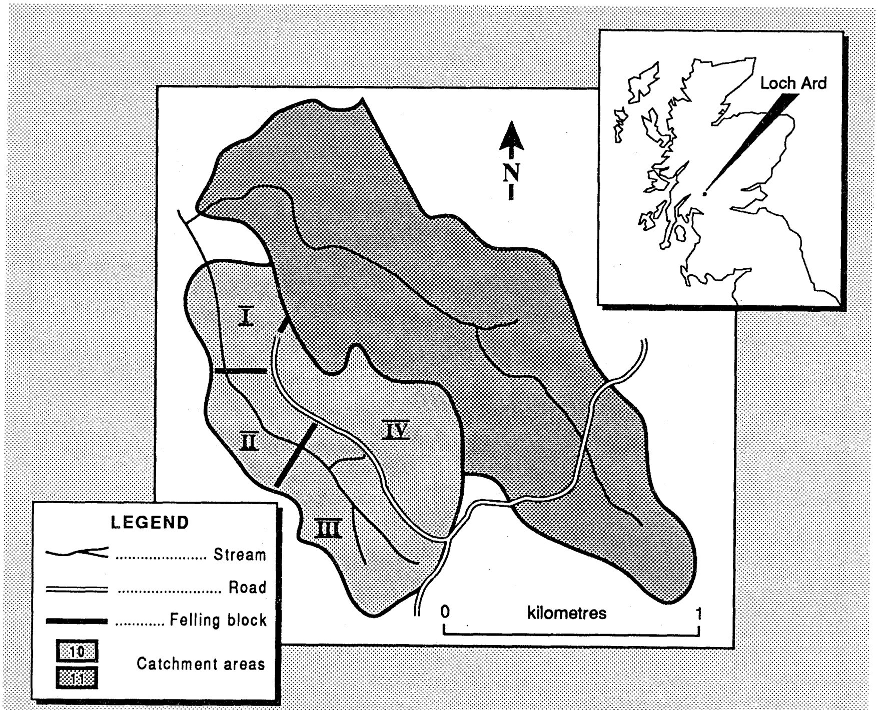

FIG. 1 Location of the study catchments.

background samples at fixed 8 h intervals. From 1988 onwards the sampling interval was fixed at 4 h in the experimental stream 10. An 8 h interval was used in the control stream 11, because of its larger catchment area and less flashy response to rainfall events. Samples of 800 ml volume were collected weekly and suspended sediment concentrations (SSC) were determined gravimetrically by filtration through Whatman GF/C filters and drying at 1000°C. 4170 determinations of SSC were made on the experimental stream between February 1987 and May 1990, and 2400 on the control between June 1987 and May 1990.

RESULTS

Figures 2 and 3 show the variation in SSC during the study period in the felled (no. 10) and control (no. 11) streams respectively. Concentrations in both streams varied over several orders of magnitude. In the experimental stream (Fig. 2) there was a pronounced increase in SSC during the first three months of the felling period (months 13-15), and maximum concentrations in excess of 1000 mg l^{-1} occurred on several occasions during February 1988 (month 14). SSC measured from month 16 onwards were generally smaller than those in the previous three months, but greater than those prior to the start of felling. It is evident from Fig. 3 that months 13-15 represented a time of large SSC in the control stream also, but that concentrations after this time were generally similar to those recorded in 1987.

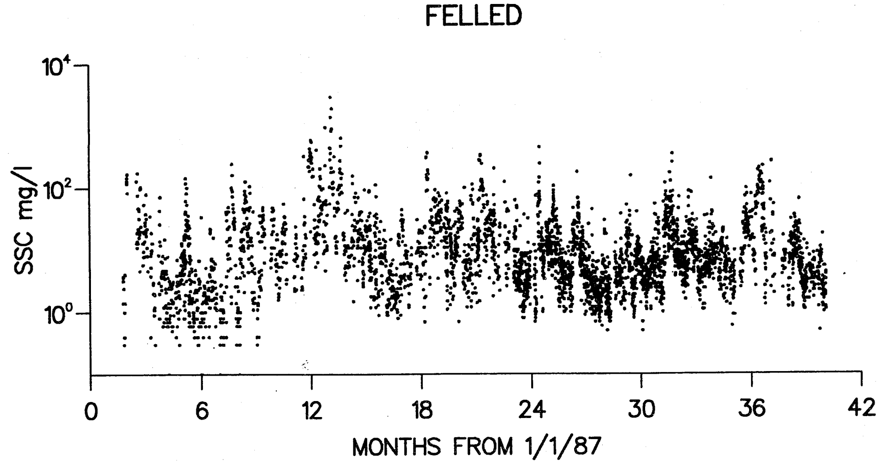

FIG. 2 SSC variations in the experimental stream.

To examine the significance of the temporal variations in SSC in the two streams, discharge-weighted mean SSC was calculated for successive three-month periods. Means, standard errors and mean discharge in stream 10 are shown in Fig. 4. Quarter-year mean discharges in the two streams were very closely correlated ($r^2 = 0.97$) and the stream 11 mean was used to infill missing data in stream 10 and vice versa for one quarter in 1987 in each stream. From Fig. 4 mean SSC in stream 10 was greater than that in stream 11 even in 1987 prior to the start of felling, thereby casting some doubt on the suitability of the latter as a control. The first three months of 1988 were marked by a very large increase in stream 10 SSC, in comparison both with the same stream in 1987 and with stream 11 in the same

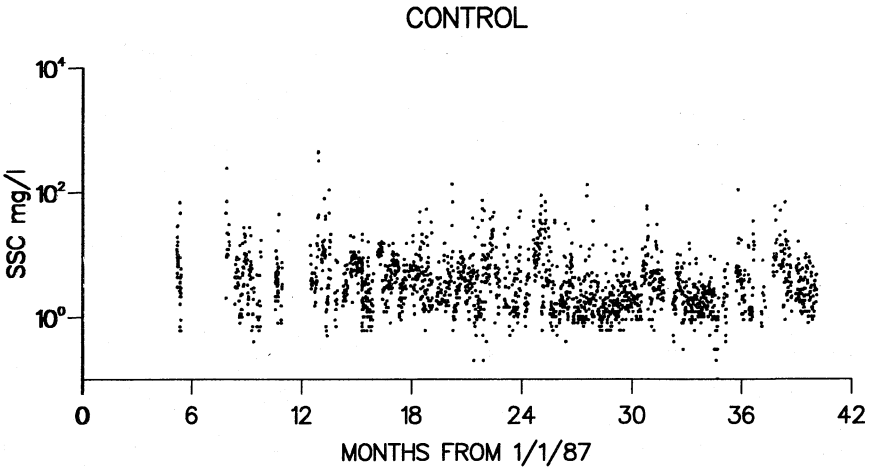

FIG. 3 SSC variations in the control stream.

quarter. April-June in both 1988 and 1989 had small mean discharges, small SSC in both streams, and a reduced ratio of stream 10 SSC to that in stream 11. During the second half of 1988, SSC in stream 10 was large both in absolute terms and relative to that in stream 11, but in 1989 and 1990 the ratio of SSC in the two streams was similar to that in 1987. It is thus clear that both discharge and felling influenced SSC in the two streams.

In order to eliminate the effects of discharge on stream SSC, regression equations of log(SSC) on log(Q) were examined. Some quarter years had a very small range of discharge, so the 12 quarters were grouped into six phases for this analysis. Phase I was the pre-felling phase in 1987 and phase II the initial bankside clearance between January and March 1988. Phases III, IV, and V, April-December 1988, January-June 1989 and July-December 1989 respectively, were the main periods of felling and extraction. Phase VI from January-April 1990 was the initial post-disturbance period.

TABLE 1 Regression equations of log(SSC) on log(Q) for the six phases in the experimental stream.

	equation	r^2	s_b
Phase I	log(SSC) = 0.06 + 0.64 log(Q)	0.395	0.04
Phase II	log(SSC) = 1.10 + 0.31 log(Q)	0.075	0.08
Phase III	log(SSC) = 0.43 + 0.38 log(Q)	0.147	0.03
Phase IV	log(SSC) = 0.24 + 0.36 log(Q)	0.203	0.02
Phase V	log(SSC) = 0.37 + 0.43 log(Q)	0.317	0.02
Phase VI	log(SSC) = 0.06 + 0.51 log(Q)	0.193	0.05

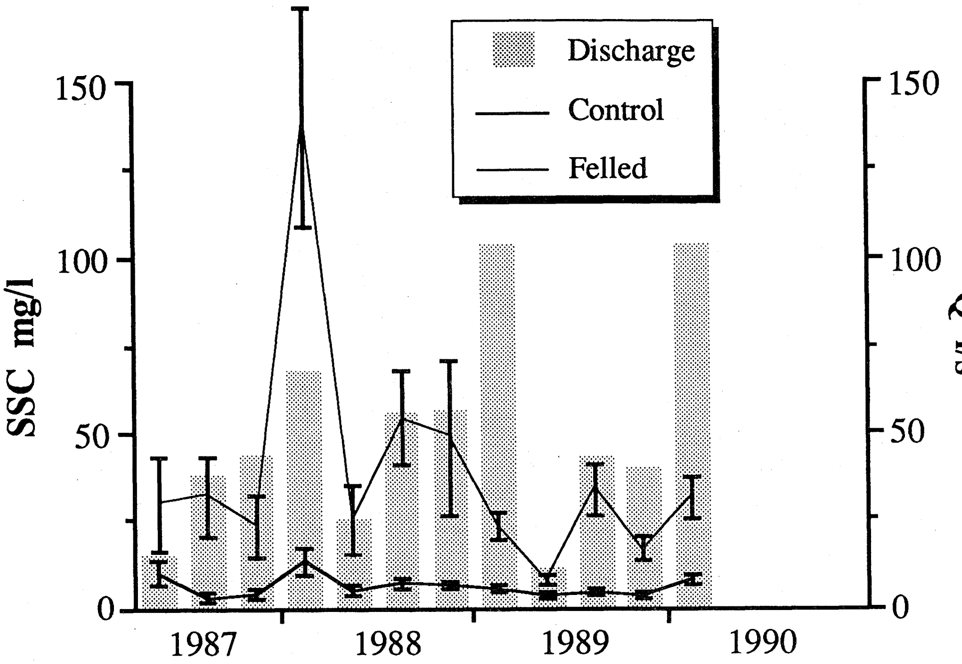

FIG. 4 Discharge-weighted mean SSC ± standard error in the two streams and mean discharge in stream 10 for successive three month periods.

Table 1 shows a systematic pattern of variation in the relationships between log(SSC) and log(Q) in the experimental stream. In the pre-felling phase (I) the relationship was strong with large r^2 and slope. Phase II was marked by a very small r^2 and slope, both of which then increased in a regular manner during the remainder of the study period. It would appear from the regressions that the major effect of the felling in the experimental catchment has been to increase SSC relative to discharge, but that this increase occurred principally at small discharges. SSC at large discharges remained relatively constant despite the felling. Relationships between log(SSC) and log(Q) in the control stream are not tabulated, but displayed no systematic variation during the study period. This adds further weight to the suggestion that felling was a significant cause of the increases in SSC in the experimental stream.

Sediment yields from both catchments in each of the six phases of the study have been calculated by two different methods in view of the well known uncertainties in estimating river loads (e.g. Walling & Webb, 1981; Ferguson, 1987). The first method used the product of sample discharge-weighted mean SSC (as plotted in Fig. 4) and mean discharge from the continuous record (method 4 of Walling & Webb, 1981). This method is theoretically unbiased if sampling is independent of discharge, which was the case in this study apart from some preferential sampling of high flows in phase I. The second method used here was the application to the continuous discharge record of a sediment rating curve of form $SSC = a Q^b$ fitted to the sample data by least squares regression of log(SSC) on log(Q) (Table 1), and then corrected for detransformation bias as suggested by Ferguson (1986). This gives an approximately unbiased estimate if the SSC v Q relationship really is a power law.

Monthly yields (t km^{-2}) of suspended sediment in each phase calculated by both methods are shown in Table 2, together with the ratios of the yields. The two methods gave very close agreement in their estimates. Sediment losses from the experimental catchment were greatest during phase II, with monthly losses some 10 times those in the pre-felling phase. Yields in the later felling phases and in the post-disturbance phase were smaller, but always greater than that in phase I. Similar variations were apparent in the control catchment, but here the phase II loss was only some 6 times that in phase I.

DISCUSSION

Effects of land use change on water quality can be assessed by comparison of paired catchments, one manipulated and the other providing a control, or by 'before and after' studies. Both techniques were employed here to quantify the effects of minimum-disturbance felling techniques on suspended sediment. Suspended sediment concentrations and yields in the experimental stream were greater during felling than before and greater in the experimental stream than in the control. However, quantification of the magnitude of the increases is complicated by variability in discharge and by the lack of true comparability of the two catchments.

*TABLE 2 Yields of suspended sediment (t km^{-2} month^{-1}) from the two catchments during the six phases of the study where CQ = Q-weighted mean SSC * mean Q, and Reg = rating curve method (bias corrected).*

Phase	Stream 10		Stream 1		Ratio 10/11	
	CQ	Reg	CQ	Reg	CQ	Reg
I	3.0	4.6	0.4	0.4	7.5	11.
II	30.	32.	2.5	2.3	12.	14.
III	6.7	4.9	0.8	0.8	8.4	6.1
IV	4.0	3.4	1.0	1.0	4.0	3.4
V	3.3	3.1	0.4	0.3	8.2	10.
VI	7.6	8.2	1.9	1.7	4.0	4.8

Differences between the two catchments in SSC and sediment yield prior to the beginning of felling cast doubt on the reliability of catchment 11 as a control. Sediment yields from both catchments during the pre-felling phase of the study must also be viewed with some caution given the limited quantity of discharge data in 1987. The two catchments were adjoining and had the same aspect and elevation, so there was probably little difference in rainfall amounts or timing. An area of peaty soils some half way down the stream draining catchment 11 may have acted as a sink for sediment lost from the upper part of this catchment, but the lower part of this catchment was similar in area to the entire experimental catchment, and should in theory have been capable of generating the same sediment yield. Bedrock was similar in the two catchments, but soils in catchment 11 were more gleyed (Macaulay Land Use Research Institute, pers. comm). It was also noted in early examination of the two catchments that the trees in the control catchment were planted further from the stream bank in catchment 11 that in 10, resulting in greater ground vegetation cover on the stream banks. These differences may have resulted in less erodible bank sediments in the control catchment. A further complication relates to the construction of the access road for timber extraction in catchment 10 during late 1986 and early 1987. Large areas of fine sediment were exposed as a result of construction, and some of this may have remained to be flushed out during the pre-felling monitoring phase in this catchment, despite the distance between the road and stream. Whatever the reason, catchment 11 cannot be regarded as a suitable control, and the effects of felling must be quantified from the change in SSC and yield over time.

This analysis is subject to further uncertainty over the effects of short-term variations in timing and amounts of precipitation. The peak SSC recorded in both streams occurred in the first three months of 1988. This was a time of particularly large rainfall and discharge, but the regression equations and the differences in yield both indicated that catchment 10 lost more suspended sediment than would be predicted from the larger discharge alone. The 90 t km^{-2} (CQ estimate) of sediment lost during the first three months of 1988 was some three times the estimated loss during the whole of 1987. That this was a time of large sediment loss due to high rainfall is not in question, since the control catchment also lost more sediment during these three months than the amount estimated for the whole of 1987. However, if the 1987 ratio of sediment losses from the two catchments had been maintained in these three months, catchment 10 would have lost some 56 t km^{-2}. The extra 34 t km^{-2} of sediment lost from the experimental catchment suggests that felling was a contributory factor. The increase may have been due to traffic in the stream bank area during wet conditions when the bankside clearance was carried out, or alternatively it may represent a flush of residual sediment from the construction of the access road in the catchment in the previous year. Whatever the cause, the early operations associated with minimum disturbance felling and extraction resulted in a very significant increase in sediment loss from the experimental catchment.

During the main felling period of 21 months from April 1988 to December 1989, the total loss of suspended sediment from the experimental catchment was 100 t km^{-2}, compared to a loss of 15.6 t km^{-2} from the control catchment. Again if the 1987 pre-felling ratio of losses from the catchments had been maintained the experimental catchment would have lost 116 t km^{-2}. This lack of significant difference in sediment losses is consistent with the regression equations (Table 1) which indicated that the main change in the relationships in the experimental catchment occurred at small discharges. It may therefore be concluded that the main period of felling had little effect on sediment yield. However if the same argument is carried forward into the post-disturbance phase the experimental catchment would have lost 60.6 t km^{-2} of sediment rather than the 30.4 t km^{-2} measured. The catchment thus appears to have recovered in terms of rate of sediment loss to a better state than that before felling within the first four months after the end of felling and extraction. This is probably not the case for two reasons. Estimates of sediment losses during the pre-felling phase probably did not represent genuine undisturbed conditions due to the possible residual impact of access road construction. Secondly, the estimate of sediment loss during the pre-disturbance phase were unreliable due to the lack of discharge data in 1987. A more accurate assessment of the impact of the disturbance must therefore be based on evidence of any further reduction in sediment losses during the recovery period.

CONCLUSIONS

The difficulties in estimating sediment losses in a paired catchment experiment are highlighted by the results discussed here. Pre-disturbance monitoring must eliminate the possibility of any preparatory work influencing sediment losses. The different losses and ratios between the catchments demonstrate the hydrologically-related variability in sediment concentrations and yields, and imply that such pre-disturbance monitoring must take place over a sufficiently long time period to quantify these short-term variations.

Bankside felling and possibly access road construction contributed to the large loss of sediment from the experimental catchment during the first three months of 1988, estimated at a minimum of 34 t km^{-2}. Losses due to felling and extraction during the main felling period were probably small, but it is not yet possible to quantify the precise magnitude of this loss.

ACKNOWLEDGEMENTS We thank the Forestry Commission for access to the catchments and for their financial contribution towards this work, Forth River Purification Board for discharge data, and Lyn Napier and Chris Anderson for analysis of several thousand bottles of water.

REFERENCES

Ferguson, R. I. (1986) River loads underestimated by rating curves. *Wat. Resour. Res.* **22**:74-76.

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

Johnson, R. C. (1988) Changes in the sediment output of two upland drainage basins during forestry land use changes. *IAHS Publ.* **174**:463-471.

Walling, D. E. & Webb, B. W. (1981) The reliability of suspended sediment load data. *IAHS. Publ.* **133**:177-194.