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Suspended sediment from two small upland drainage basins: using variability as an indicator of change

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Abstract Ten years of sediment sampling in the Balquhidder drainage basins, Scotland, has shown that variability of the suspended sediment concentrations dominates the data sets. The two basins are physically similar in all aspects except land use; the Kirkton being recently clearfelled and the Monachyle afforested. Comparison of the variability in the annual data sets with land use, climatic and hydrological changes indicate that in the Kirkton basin variability increased when the clearfelling started but variability in the Monachyle did not increase until a year after the pre-afforestation ploughing. Recovery of both basins was slowed by changes in the rainfall and runoff patterns. Standard deviations of flow determined sub-sets of the sediment data were used to compare the data from the three periods in the record: pre-disturbance, disturbance and recovery. The Kirkton showed an increase in the variability in high flows during the second and third periods but no change in low flows. The Monachyle showed an increase in variability at low flows during the second period but an increase in variability at high flows and decrease in low flows in the third period. The differences between the basins are thought to be due to the different sediment sources, with those in the Kirkton being more hillslope sources, whereas those in the Monachyle are in-channel sources. It is concluded that variability is an important component of the sediment regime and can be used to indicate changes in basins.

INTRODUCTION

Ten years of sediment sampling in two upland basins in Scotland has shown that the variability of suspended sediment concentrations dominates the data sets. The sampling was part of a water quality programme within a larger research study to determine the impacts of forest management on water resources. Early attempts to quantify the impacts of land use changes in the basins were hampered by excessive scatter in the data; severe smoothing seemed to be the only way of developing a time series, but as the data set increased the scatter emerged as being an important component of the data. Analysis of the scatter has now been carried out and systematic variability found which can be used to demonstrate the impact of changes in the basins.

Previous results from basin experiments rarely discuss the variability of the sediment data, but Guy (1965) noted that the process of erosion causes a highly variable quantity of sediment to be suspended, Walling & Webb (1987) gave an examples of excessive variability, where there was a lack of any relationship between concentration and streamflow, and Olive & Rieger (1992) reviewed a range of studies to show how natural variability in streams affects research results and how this can only be resolved by increasing the length of record.

The suspended sediment data sets for the two basins in Scotland indicate that changes have occurred during the period of sampling, but it has been difficult to quantify those changes and to identify the causes. The initial approach was to use a rating curve method (Johnson, 1988) with correction factors applied to take into account the scatter in the data (Ferguson, 1986). Temporal changes in suspended sediment-flow relationships were identified for the first few years, but scatter in the data became excessive making the further use of rating curves dubious. During the period of the experiment there were significant variations in the climate, with rainfall and flow increasing. These variations complicate the main objective of the sediment programme, which was to determine the effects of the land use changes.

This paper aims to look at variability of the suspended sediment concentrations in the Balquhidder basins, Scotland, to see if it can be used to indicate the impacts of the land use and climatic changes.

CHANGES IN THE BALQUHIDDER BASINS

The Balquhidder paired basin experiment was established in 1981 to study the effects of forest management on water resources (Johnson & Whitehead, 1993). The basins are located some 60 km north of Glasgow in the southern Highlands of Scotland. They are physically similar, some 7 km^2 in area with an altitude range from 250 to 900 m. The geology is mica schist and soils a mixture of ranker, surface water gleys and peaty gleys. The major difference between the basins is the land use, with the Kirkton basin, at the start of the experiment, supporting a 42% cover of coniferous forest and the Monachyle basin rough grazing.

In early 1986 the land uses in both basins were changed with clearfelling of the Kirkton forest and afforestation of the lower altitudes in the Monachyle. Clearfelling included the removal of tree branches on site, with the timber extracted to roads by skylines, then uplifted by articulated lorries. Afforestation included the pre-planting ploughing for drainage of the wetter ground, but leaving 15-30 m wide buffer strips in the riparian zones. Both land use changes affected relatively small areas of the hydrological basins, but this is typical of upland forestry in the UK. Table 1 includes figures for the annual areas clearfelled and afforested. Sediment sampling started in late 1982, so three years of baseline data were available before the land uses changed.

During the period of the experiment there were significant variations in the rainfall and streamflow patterns. Cumulative daily rainfall showed a significant increase in late 1986 and the mean daily rainfall intensity and frequency of 24-h rainfall totals exceeding a threshold of 30 mm (a large event in Scottish terms) both showed considerable variations in the period (Table 1). Changes were observed in the hydrological regimes of the basins, with cumulative daily runoff increasing and both mean daily runoff and the frequency of flood events in excess of 20 mm day^{-1} varying (Table 1).

The basins have therefore been subjected to changes in the land use, rainfall and runoff patterns which could potentially have had an impact on the sediment release and transport in the fluvial systems. By developing a catalogue of changes (Table 1), it was hoped to relate changes in the suspended sediments to specific events within the basins.

Table 1 Tabulation of changes in sediment variability, land use, rainfall and river flow in the Balquhidder basins for the sediment years 1983-1984 to 1991-1992.

Change	Sediment year: 1983-84	1984-85	1985-86	1986-87	1987-88	1988-89	1989-90	1990-91	1991-92
1	5.5	4.9	9.5	10.2	12.8	12.8	12.9	13.7	14.9
2	108	45	125	367	62	499	500	207	244
3	10.0	10.7	10.3	10.1	14.6	13.0	12.0	12.3	12.2
4	22	38	39	51	132	85	186	100	116
5	0	0	4	60	19	25	17	0	0
6	0	0	40	5	0	0	0	0	0
7	8.3	9.0	10.9	8.5	9.1	9.8	11.1	9.3	10.3
8	199	193	186	223	237	232	215	211	222
9	10	8	20	9	11	12	19	16	15
10	4.6	4.3	6.7	5.0	4.7	6.7	6.4	4.8	-
11	9	6	22	16	9	20	21	15	-

Changes:
1 Area of parallelogram (Kirkton);
2 Standard deviation of suspended sediment concentrations (Kirkton), mg l^{-1};
3 Area of parallelogram (Monachyle);
4 Standard deviation of suspended sediment concentrations (Monachyle), mg l^{-1};
5 Kirkton area of clear felling, ha;
6 Monachyle area of ploughing, ha;
7 Mean daily rainfall intensity, mm;
8 Number of rain days;
9 Number of days with rainfall > 30 mm;
10 Mean daily runoff (mm);
11 Number of days with runoff > 20 mm.

CHANGES IN THE SUSPENDED SEDIMENT REGIMES

The 1983-1992 time series of suspended sediment concentrations for both basins (Fig. 1) show that the data are dominated by the variability and it is very difficult to determine any changes or trends in the mean values. Some 4000 samples were taken in each basin over the 10 year period, which is likely to provide a sample large enough to represent the true distribution (Johnson, 1992). Suspended sediment concentrations are generally greater in the forested Kirkton basin compared to the Monachyle basin, the 10-year mean concentrations being 114.7 and 43.7 mg l^{-1}, respectively. In terms of the scatter of points, the standard deviations of the data are also higher for the Kirkton compared to the Monachyle, 352.3 and 117.6 mg l^{-1}, respectively.

Due to the large variability in the data, envelopes were constructed around the data to indicate the extreme values throughout the data set. This was carried out manually on a stepwise basis for both basins, independently and with no consideration of basin or

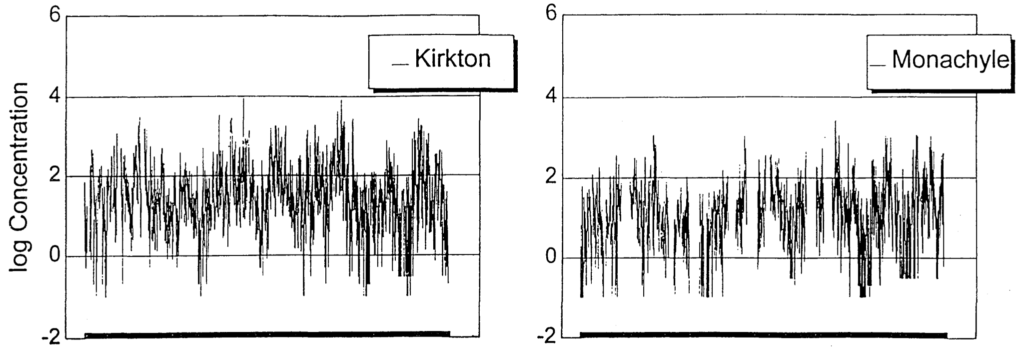

Fig. 1 Time series of the suspended sediment samples for the Balquhidder basins, 1983-1992 (concentration in mg l^{-1}).

climatic changes. When the envelope changed appreciably due to the addition of a further group of data then this was noted as a break in the time series and a new envelope started. This can be somewhat subjective and needs an honest approach to the analysis. The results were that four periods were identified for the Kirkton basin and five for the Monachyle basin, with the breaks between the periods occurring around the time of a summer low flow period. This result suggested that the sediment regimes of the rivers were reacting on an annual time cycle, starting and ending at the time of a prolonged dry period. Consequently the data for both basins was subdivided into sediment years stating on 1 June and finishing on 31 May.

Quantification of the sediment envelopes was difficult, so each one was simplified by drawing parallelograms around the data, fixed in the horizontal by flow limits and manually drawing a straight line which best encompassed the extremes of the data. Two of the sediment years (1984-1985 and 1991-1992) are shown in Fig. 2. The areas of each parallelogram were calculated from the sediment concentration which each corner represented (Table 1).

The results of the parallelogram analysis show that area, and hence the scatter of the extreme values, in the Kirkton increased in the years when felling occurred, but in the later years, when the felling temporarily stopped, the scatter increased again. In the Monachyle, scatter increased over a year after the ploughing was carried out then decreased, but remained at a higher level than during the pre-disturbance years.

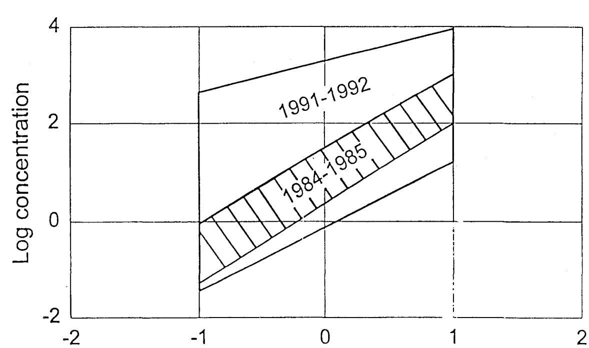

Fig. 2 Examples of the parallelogram analyses for the Kirkton basin containing the extreme data points in the two years 1984-1985 and 1991-1992.

VARIABILITY, SCATTER AND LAND USE CHANGE

Variability is a rather loose term which has been used here to indicate scatter. For these sediment data, a statistical term was sought to represent variability so that consecutive sediment years and the basins could be compared. Various options were available but it was considered most appropriate to select one widely used term and not broaden the analysis to find terms which may misrepresent the data; standard deviation was the term selected. For each sediment year a number of analyses using different data sub-groups, such as low flows and high flows, were tried, details of which can not be included here due to lack of space.

Table 1 is a selection of the sediment year calculations for the period 1983-1984 to 1991-1992 and provides a summary of the most relevant results. To represent the variability in the data, both the area of the parallelograms and the standard deviation of the annual data are presented to be compared with results for land use changes, climatic and hydrological variations.

A comparison of the data in Table 1 shows that there was no simple and consistent relationship between the sediment concentration variability and the basin data. The first three years of the study contained a mixture of climatic years with 1983-1984 and 1984-1985 having few storms, but 1985-1986 having many more, the storms in the third year mostly occurring in the months prior to the land-use changes. There appears to be no reaction in the Monachyle sediment regime to the climatic variability before the land uses changed but the Kirkton showed an increase in variability in 1985-1986, even though the clear felling did not start until after the storms occurred. This suggests that the Monachyle basin had a natural protection against more extreme climatic years, but the Kirkton had less natural protection possibly due to the past afforestation.

The parallelograms showed a two phase increase in the Kirkton, but a single peak in the Monachyle. The first changes in the Kirkton parallelogram occurred over the period 1985-1988, initially associated with the frequent storms but later with the clearfelling. The second increase in 1990-1992 can not be related to any new land-use changes as no clearfelling occurred in these years. There was, however, an increase in the mean daily rainfall intensity in this period, and although other climatic factors changed, none appears to provide a good explanation for the second increase in the parallelogram area. The Monachyle showed an increase in the parallelogram area in 1987-1988 over a year after the ploughing, then a decrease for the last three years, but not back to the background levels. It is likely that the one year delay was due to the ploughing occurring in a relatively storm free year, but once the next year's storms had fully activated the plough lines the following years remained more variable than before the disturbance.

The standard deviation of the data in each sediment year for both basins again show increases which can be related to the land-use changes, with the Kirkton reacting immediately and the Monachyle being delayed by over a year. The Kirkton results are in general agreement with previous work, for example Burgess *et al.* (1981) who found that there was an immediate reaction to logging operations in Australia. The Monachyle results differ slightly from other results, for example Robinson & Blyth (1982), who found an immediate reaction to pre afforestation ploughing. Peaks in the Kirkton standard deviation occurred in 1986-1987, 1988-1989 and 1989-1990, the first of which can be related to the land use but others more closely to the number of large storm and runoff events. The Monachyle standard deviation peaked in 1987-1988, due to the land use, but again in 1989-1990, again probably due to the storm events.

The above analysis can only be indicative of the cause and effects in the sediment regimes, but with land use, climate and hydrology all changing it remains extremely difficult to separate the effects.

VARIABILITY AS AN INDICATOR OF CHANGE

The previous section identified three contrasting periods in the Kirkton and Monachyle basins over the 10 years of monitoring: a 2 (Kirkton) and 4 (Monachyle) year baseline period followed by a 3 (Kirkton) and 1 (Monachyle) year period of reaction to land uses and finally a 4 year period in both basins of recovery from land-use changes, but reaction to climatic changes. For comparison between the two basins these three periods have been standardized to the years 1983-1985 (period 1), 1985-1988 (period 2) and 1988-1992 (period 3). For each period the suspended sediment data were subdivided into groups according to the stream flow at the time of the sample.

Results of the group analysis showed that, in general, there was an increase in the standard deviation with flow, with the Kirkton having a closer relationship than the Monachyle. Results for the three periods were very different (Fig. 3): the standard deviations at high flows in the Kirkton increased in successive periods, but at low flows

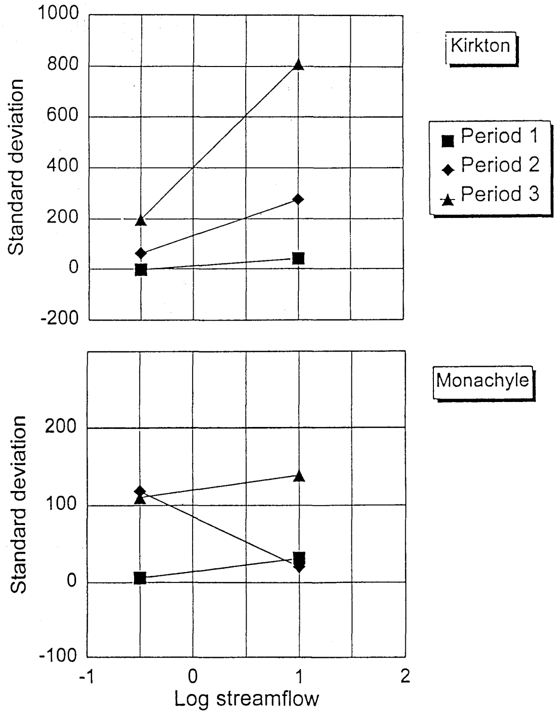

Fig. 3 Regression lines of the relationships between standard deviation of the suspended sediment samples and streamflow for the periods pre-disturbance (period 1), disturbance (period 2) and recovery (period 3).

showed no change, while in the Monachyle the second period showed an increase in standard deviation at low flows, but little change in high flows resulting in a reversed relationship with flow. In the third period the relationship reverted back to being parallel to, but shifted above, period 1. The above results differ from the parallelogram analysis, in that the later showed an increased scatter in all flow ranges; this is the contrast between looking at the whole sample in the flow range with standard deviation, but only the extreme values with the parallelograms.

Comparing the standard deviations for the two basins the first period showed relatively small differences compared to the subsequent two periods. In periods 2 and 3, the main impact of basin changes in the Kirkton were confined to the high flow samples, but in the Monachyle the high flow samples were only affected in period 3, and low flow samples only in period 2. The change in the relationship and the contrast between the basins was substantial and it is considered that the cause was due to the land use changes creating new, but different, sediment sources. The main new source in the Kirkton was on the clearfelled hillslopes, which are only linked to the river system during storm events, while the new Monachyle sources were within the drainage system where a limited supply of material was removed in the lower flows, leaving little available for transport in the higher flows.

CONCLUSIONS

The main results of this work are:

(a) The forested basin had the greater suspended sediment variability before the land uses changed, as the moorland basin appeared to be naturally protected against storm events.

(b) The standard deviation of the samples and the envelopes containing the extreme data points showed a progressive change in response to both the land-use and climatic changes.

(c) The land-use changes increased the variability in the data, at high flows in the Kirkton and low flows in the Monachyle. This was seen as the land use creating new, but different, sources of sediment in each basin.

(d) Climatic extremes after the land use changes had a greater impact than similar events before. This was due to the land use changes destabilizing the basins, possibly for a very long time.

(e) Variability can be used as an indicator of change, but long data sets are required.

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